VEHICLE NOISE SOURCES AND NOISE-SUPPRESSION POTENTIAL

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Table 1 gives the origins of noises that disturb people in their homes. Highway noises are cited as being annoying by 20 to 30 percent of the people. The London survey sample (1) was drawn from more than 400 sites uniformly distributed but generally located away from aircraft noise. The Chicago and Minneapolis-St. Paul survey samples (2) were drawn from a cross section of the cities and included sonic boom complainants. Surveys in the 4 eastern and 4 western cities (3) included people who were within an area subject to substantial amounts of airport noise. Certain obvious differences, therefore, appear among the transportation categories, particularly the amount of dissatisfaction directed toward aircraft operations. Significantly lower annoyance due to aircraft is shown by the London data than by the other data; and, not too surprisingly, higher annoyance levels are shown by communities near airports than by communities in the sonic boom cross-sectional survey.

Table 2 gives some vehicle population and use statistics. Since each vehicle is a noise source, the sheer number of motor vehicles and the magnitude of vehicle-miles per year tend to explain some of the public outcry about traffic noise. More than 84 million automobiles, 17 million trucks, and 2 million motorcycles interject a continual stream of noise into residential areas. Data in this table also indicate the increasing use of highway vehicles within the urban community; 1985 projections indicate almost a

Table 1. Percentage of people annoyed by and sources of residential noise.

Noise Source	London[a]	Chicago[a]	Chicago[b]	Minneapolis-St. Paul[a]	4 Western Cities[b]	4 Eastern Cities[b]
Aircraft	9	37	40	33	39	62
Road traffic	36	36	26	29	24	33
Trains	5	7	7	3	3	3
Bells, alarms, and sirens	3	8	6	15	14	17
Industrial and construction	7	3	2	6	2	6
Other people	19	33	32	32	26	20
(children)	(8)	(18)	(13)	(13)	(14)	(9)
Pets and animals	3	10	8	13	13	15
Number surveyed	1,400	1,064	872	901	3,590	3,217

[a]City cross section. [b]Airport environs.

Table 2. Population and use of mobile noise sources in United States.

Source	1968 Number in Use	1968 Use	1985 Number in Use	1985 Use
Automobiles	84,000,000	9,000 miles/vehicle/yr (55 percent urban)	130,000,000	9,000 miles/vehicle/yr (65 percent urban)
Trucks	17,000,000	12,000 miles/vehicle/yr (40 percent urban)	28,000,000	12,000 miles/vehicle/yr (50 percent urban)
Buses	350,000			
Motorcycles	2,000,000		9,000,000	
Tractors and construction equipment	2,000,000			
Aircraft	150,000	80,000,000 operations	317,000	430,000,000 operations
Commercial	2,900			
General aviation	120,000			
Military	30,000			
Trains				
Locomotives	29,000			
Cars	1,800,000			
Boats				
Outboard motors	7,000,000			
Pleasure boats	4,000,000			
Ships and towboats	5,000			

Note: 1 mile = 1.6 km.

Table 3. Miles traveled by motor trucks.

Truck	Year Registered	Trucks Registered	Miles Traveled	Average Miles Per Vehicle
Single-unit	1965	14,008,000	140,117,000,000	10,003
	1966	14,694,000	140,893,000,000	9,588
	1967	15,363,000	147,450,000,000	9,598
	1968	16,124,000	158,938,000,000	9,857
	1969	16,942,000	167,241,000,000	9,871
Combinations	1965	787,000	31,319,000,000	39,759
	1966	823,000	33,012,000,000	40,112
	1967	830,000	35,006,000,000	42,176
	1968	871,000	37,713,000,000	43,299
	1969	929,000	39,439,000,000	42,453
Total	1965	14,795,000	171,436,000,000	11,587
	1966	15,517,000	173,905,000,000	11,207
	1967	16,193,000	182,456,000,000	11,268
	1968	16,995,000	196,651,000,000	11,571
	1969	17,871,000	206,680,000,000	11,565

Note: 1 mile = 1.6 km.

doubling of urban vehicle-miles compared to 1968. One could presume that this means only a 3-dB increase in the highway noise level (which is almost imperceptible). The projected increase, however, will result from increases in the number of miles of high-speed roadway travel and possibly an increase in average vehicle speed. That combination will produce more than the nominal 3-dB increase in noise level in communities now exposed and will expose many new communities not now subjected to significant highway noise.

Table 3 gives the miles traveled and the number of trucks registered each year between 1965 and 1969. Although combination trucks represent a small portion of the total highway population of vehicles, the number of miles they travel each year is significant; each vehicle operates on the average 42,000 miles (67 200 km) per year. This has implications in terms of the alternatives to reduce the noise generated by these heavy vehicles.

Figure 1 shows the average speed of highway vehicles and the percentage of those exceeding 50 mph (80 km/h). Both continually increased between 1942 and 1968. Recently, fuel shortages have caused nationwide reductions in highway speed limits so that the gradual increase in average vehicle speeds has been temporarily reversed. Indications are, however, that average speeds are again climbing.

The average age of motor trucks in the United States must also be considered in noise-abatement strategies. Figure 2 shows that a great number of motor trucks are 5 to 10 years old. More than 25 percent of all trucks are older than 10 years.

The range of problems one encounters in categorizing highway noise sources is shown by Figure 3 (4). Two things are immediately evident: (a) As speeds increase, the noise levels generated by automobiles and trucks increase and (b) trucks produce higher sound levels than automobiles do. Figure 3 also shows that the ranges of sound levels generated by these vehicles overlap when the noisiest in one category is compared to the quietest in the next category. That is, the noisiest 10 percent of automobiles generated as much noise on streets as did the quietest 30 percent of motorcycles or trucks at speeds of 35 mph (56 km/h) or less. In general, however, trucks are the dominant noise source on highways.

TRUCK NOISE

Figure 4 shows the noise sources of a heavy-duty diesel tractor trailer. Figure 5 shows sound levels of the major noise sources measured 50 ft (15 m) to the side of the vehicle. Two levels are shown for tire noise because of the speed dependence of this source. This type of presentation is possible for diesel trucks because of the insensitivity of the first 4 noise sources to vehicle speed. They are dependent on engine speed (rpm), but the large array of gear ratios provided in most diesel trucks results in a narrow range of engine speed during typical operations.

Engine noise produced by the rapid pressure rise in the combustion chambers of such engines is radiated by the vibrations of the engine block and attached fixtures. A sound level of 78 dBA has been attributed to the engine and mechanical combustion noise sources.

Exhaust noise is engine noise radiated from the exhaust pipe outlet and vibration noise of the pipes and mufflers. A level of 85 dBA is shown to represent typical exhaust noise.

Engine air intake or induction noise is created by the pulsating column of air moving into the engine and, in many cases, includes noise of mechanically driven or exhaust turbine-driven supercharges. A relatively low level of 75 dBA is generated by the induction process.

The engine cooling fan moves large quantities of air through the radiator with a very restricted downstream flow condition and generates high noise levels. Fan noise, 82 dBA, is second only to engine exhaust noise.

Tires generate a noise level of 75 dBA at a speed of 35 mph (56 km/h) or less and 95 dBA at highway speeds.

Adding all sources gives a total truck noise level of 88 dBA at speeds less than

Figure 1. Speed trends on main rural highways by vehicle type.

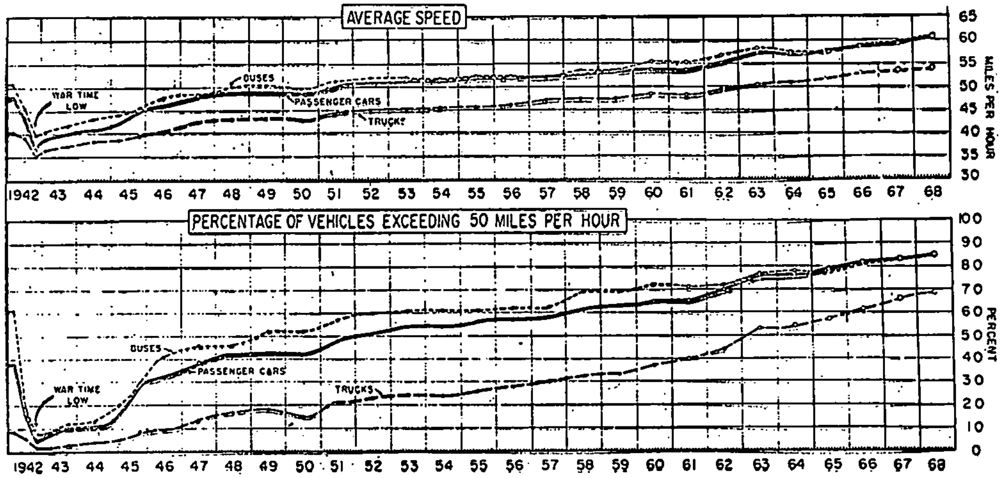


Figure 2. Motor trucks in use by age groups.

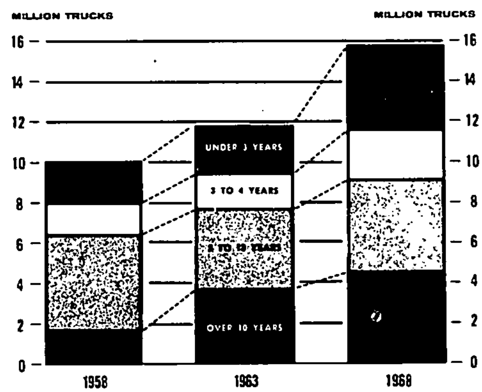


Figure 3. Results of 1971 California noise survey.

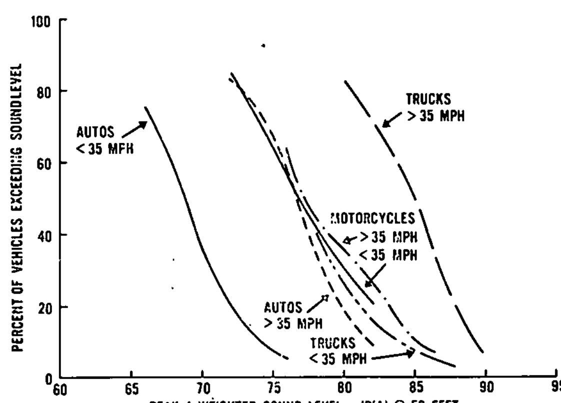


Figure 4. Truck noise sources.

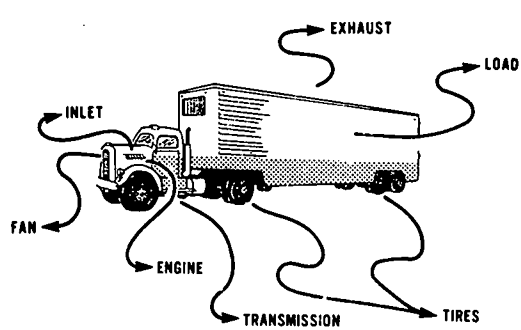


Figure 5. Diesel truck noise sources.

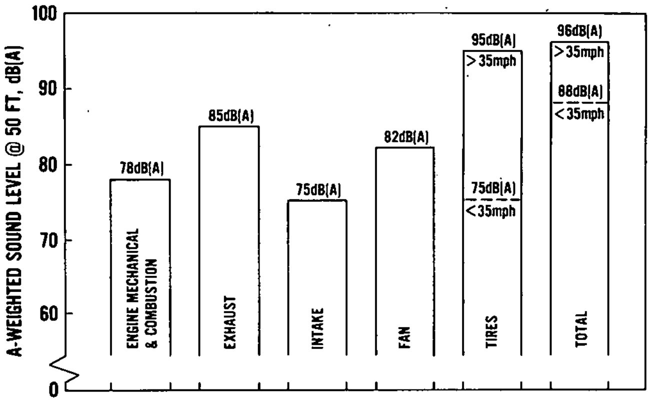


Figure 6. Effect of speed on truck tire noise.

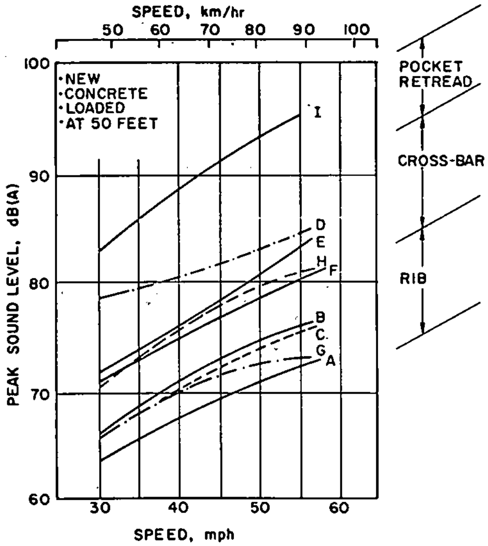
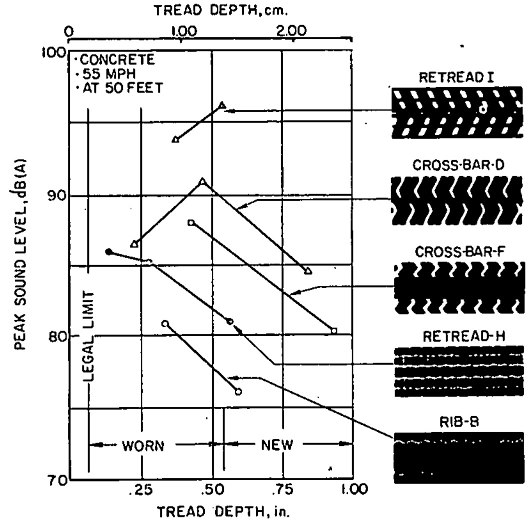


Figure 7. Effect of wear on truck tire noise.



35 mph (56 km/h) and 96 dBA at highway speeds. These data would apply to a relatively modern truck design that is in compliance with voluntary industry standards and noise regulations of various states and localities. Half of the large trucks today, however, have either inadequate muffling or no muffling at all, and that makes exhaust noise for normally aspirated engines (not turbocharged) considerably higher than that shown on this figure.

The problem is obvious: to reduce the noise level of these loud vehicles. Suppose a hypothetical truck has a completely silent exhaust. That is, the noise level of 85 dBA shown in Figure 5 for exhaust noise is reduced to zero. In this case, the highway noise level of the truck is diminished by approximately ½ dB, clearly imperceptible to a roadside observer. Complete elimination of the exhaust noise would, however, benefit the urban dweller (where vehicles typically operate at low speed generating lower tire noise) by reducing the total vehicle noise from 88 dBA to 85 dBA. Such a small reduction of 3 dB in the urban environment, however, is not a significant improvement because trucks are 8 dB louder than automobiles on the average. It is evident, therefore, that a concerted attack on all sources of noise emanating from these heavy trucks must be made simultaneously to reduce the noise level to values that are sought by legislators and expected by residents of communities adjacent to the highways.

Truck Tire Noise

Results of research of the U.S. Department of Transportation are presented. Nine distinctly different tread patterns, which represent the more popular tires used by industry today, were tested. Figure 6 shows truck tire noise levels as a function of speed for a variety of new truck tires operating on a concrete, semipolished surface, loaded to typical state load limits. Sound levels measured at the 50-ft (15-m) sideline position are presented as the peak A-weighted sound level. Four test tires were mounted on the drive axle of a single-drive-axle flatbed truck, which in turn coasted past the microphone with the engine turned off and clutch disengaged. Sound levels shown, therefore, are those generated solely by the tires of the vehicle. Test tire A was the quietest of all commercially available tires and was used on the steering axle for all tests. Rib tires were significantly quieter than cross-bar tires, which in turn were significantly quieter than certain pocket retread tires. Variation of sound level as a function of speed and tire type is clearly shown in Figure 6.

Figure 7 shows the effect of tread wear on sound levels. The data points at the extreme right indicate the tread depth of each tire when it is new or newly recapped. As the tire wears, the tread depth decreases and the sound level increases for all tires with the exception of the pocket retread I. The decrease in sound level resulting from wear of retread I is believed to be directly related to the decreased volume of the suction cup cavities. These cavities are indicated by the white areas in the patch print. As the tread wears, this cavity volume is reduced and the sound level decreases, for the cavity suction is the most significant noise generator for this tread pattern. Also the question of vibration input to the noise generation process must be considered. The increased tread element stiffness resulting from tire wear enters into the equation in some as yet undetermined fashion.

Figure 8 shows the effects of axle loading on the noise generated by 4 test tires. Two-point curves are drawn representing the empty vehicle and the typical state axle limit of 17,000 lb (7650 kg). Significant variations in sound level are generated by changing this one variable at a constant vehicle speed of 55 mph (87 km/h).

Figure 9 shows the effects of road surface on the sound level of a variety of new and worn truck tires. The road surface descriptors have been arbitrarily spaced across the abscissa, for it is not known what critical surface variable controls the noise levels produced. The suction-cup tires become significantly quieter on rough surfaces where the tread pockets cannot seal to the road surface effectively. Cross-bar tires are relatively insensitive to road surface, but rib tire noise increases as road roughness increases. The road roughness increases the vibration forcing function

Figure 8. Effect of axle loading on truck tire noise.

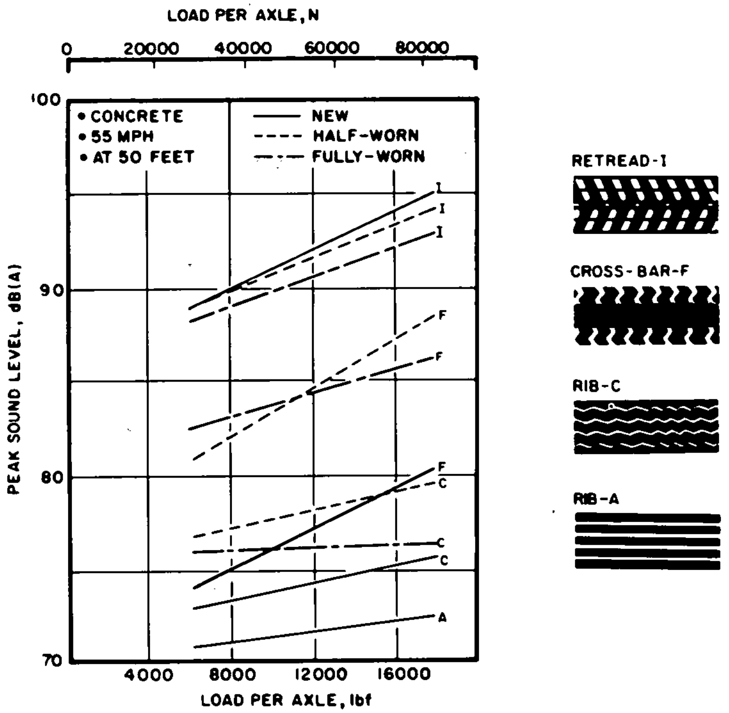
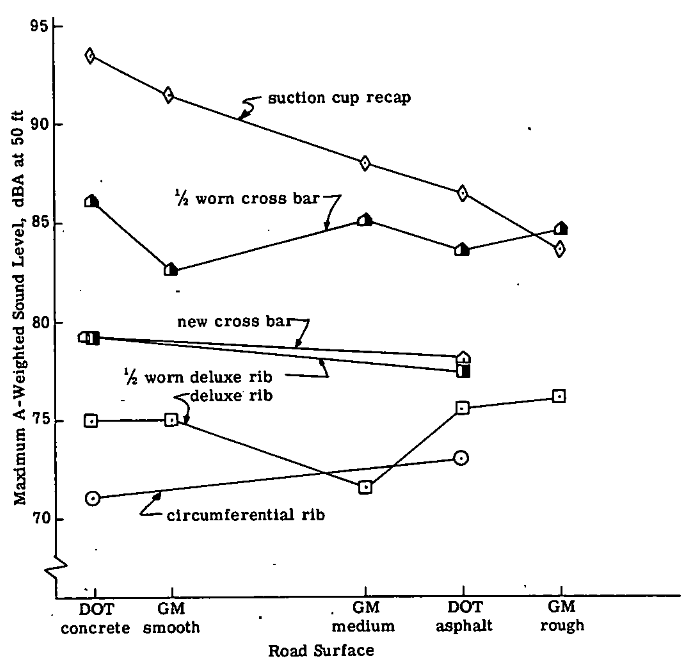


Figure 9. Effect of road surface on truck tire noise.



for rib tires, but the tread elements of the cross-bar tires simply overpower the comparatively small-scale road surface features of the range of roads tested.

Figure 10 shows a narrow-band analysis of the sounds generated by a truck tire at 50 mph (80 km/h). A fundamental tone at 360 Hz is a dominant portion of the spectrum, and a harmonic is indicated at 720 Hz. In between, broad-band noise is generated by the smaller tread elements and road surface texture.

Diesel truck noise sources excluding tires are shown in Figure 11. This shows important sources of noise for speeds below 35 mph. The dashed lines indicate what is possible with the application of known technology for retrofitting present production vehicles. A 10-dB improvement in exhaust noise and a 5-dB reduction in intake noise through the application of improved muffler and air cleaner combinations and 6- to 7-dB improvement in fan noise are believed possible on present vehicles without significantly degrading the performance or economics of the vehicle. The total noise level, therefore, of 81 dBA at 50 ft (15 m) under maximum acceleration conditions is achievable and has been demonstrated under research by the federal transportation department.

Truck Intake and Exhaust Noise

Figure 12 shows the exhaust noise at 50 ft (15 m) for a variety of 2- and 4-stroke diesel engines as a function of engine rpm. The unmuffled engine generates a cacophony of sounds reaching ear-shattering proportions. A typical range of muffling extends from 20 to 30 dB, which reduces the judged loudness of the muffled sounds to a fourth to an eighth of the unmuffled sounds. Apparently, a significant option is available for noise reduction by simply reducing the engine speeds. Unfortunately, the typical diesel engine generates its maximum horsepower (wattage) at higher engine speeds, and all of the horsepower is required to operate the truck and maintain the flow of traffic on the highway.

Figure 13 shows the sound level reduction that can be achieved as a function of ratio of muffler diameter to exhaust pipe diameter. The lower curve denotes the basic volume attenuation achieved by the expansion chamber effect of a properly placed muffler in an exhaust system. The upper curve indicates the improvement that can be made by placing the proper elements in the volume of the muffler. This is the "black art" of the muffler acoustician. Present mufflers range from 20- to 30-dB attenuation with ratios of muffler diameter to tube diameter of 2 to 3. Adding length to the present diameter ratio will increase the attenuation as indicated on the right, and increasing muffler diameter will continue to provide further increases in muffler attenuation.

Of paramount importance in muffling exhaust systems of diesel trucks is the back pressure of the exhaust system (from exhaust manifold to ambient pressure). Manufacturers' engine warranties are specific on the point that installation of engines requires that low back pressures at the manifold not be exceeded. In addition to the engine warranty problem, power is significantly degraded by increased back pressure. Engine valve deterioration is also attributed to excessive back pressure. Therefore, the problem is to develop mufflers that have low back pressure, are acoustically effective, meet present weight and space limitations of diesel trucks and buses, and cost only reasonably more than the present mufflers.

The right ordinate in Figure 13 indicates the degree of efficiency of present muffler technology in terms of the percentage of sound power emanating from the engine that is attenuated by the muffler in achieving 20 to 40 dB of sound reduction as indicated on the left ordinate. Forty decibels, for example, requires 99.99 percent of the sound to be attenuated by the muffler. This efficiency has been demonstrated, and only packaging technology and regulation are required to bring it into practice. The basic parameters also apply for the intake induction muffler. Most trucks have an efficient air cleaner on the induction side of the engine, which happily provides a fair degree of muffling. However, in the balanced noise reduction approach that must be taken, additional muffling must be designed into the induction system and, particularly, in turbocharged and supercharged diesel engines, where significantly higher induction

Figure 10. Narrow-band analysis of truck tire noise.

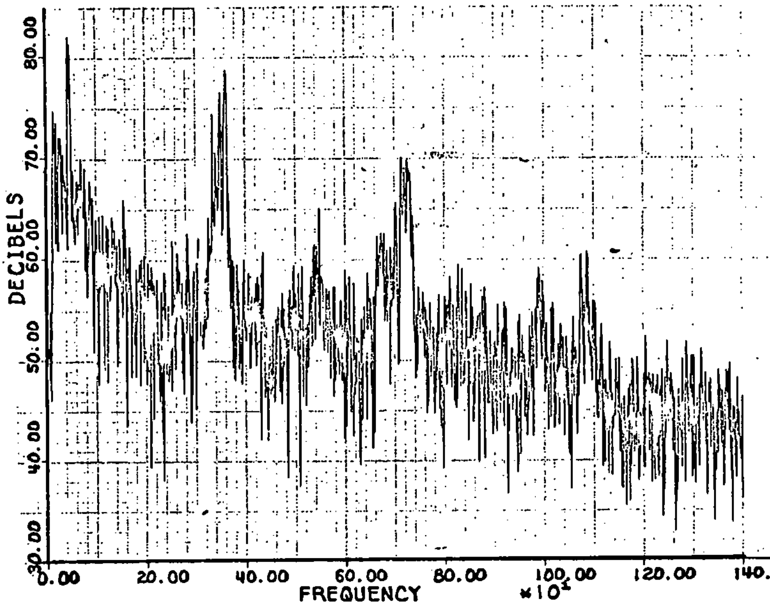


Figure 11. Diesel truck noise sources, excluding tires.

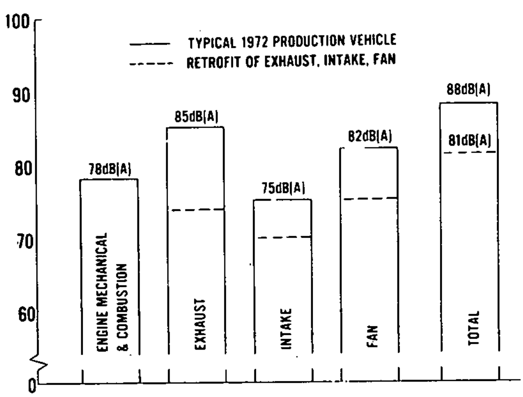


Figure 12. Diesel engine exhaust noise.

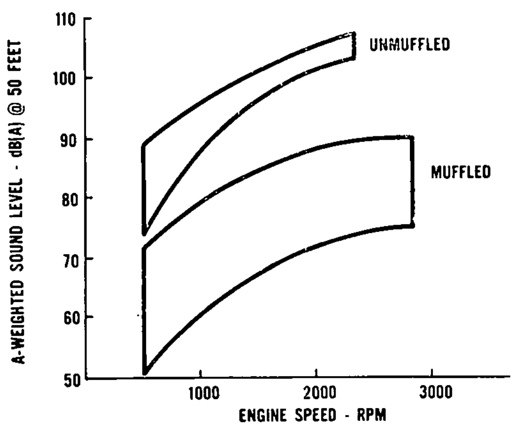


Figure 13. Intake and exhaust muffler effectiveness.

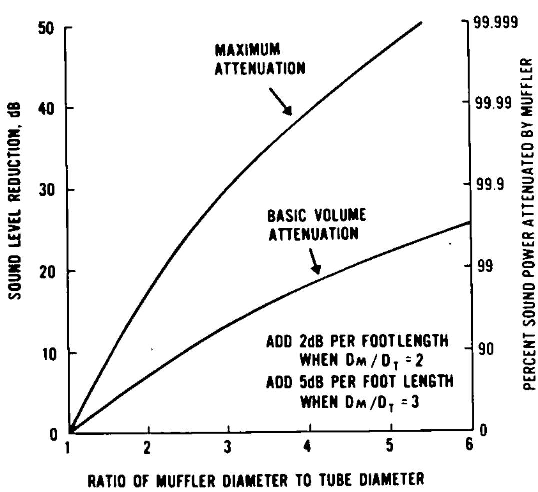
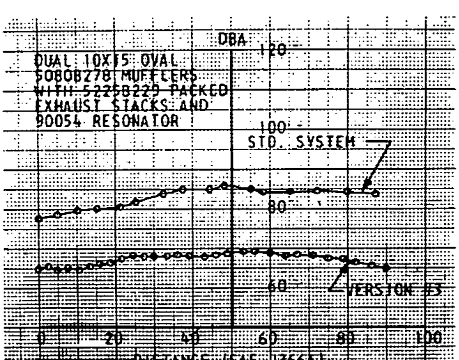


Figure 14. Truck noise with and without muffler and exhaust stack silencer.



noise levels are generated.

Several factors are particularly important in considering the balanced reduction of heavy-duty diesel truck noise. One is the low frequency of the exhaust noise that propagates more efficiently than the higher frequency noise and that couples more efficiently with structures and provides, therefore, secondary radiation such as dish rattling. Of perhaps greater importance, typical diesel exhaust and induction stacks are located 10 to 13 ft (3.5 m) above the road. This is an important factor in the application of highway noise barriers, which would have to be very high to be effective in handling these components of the overall truck noise. All of the other truck noise sources emanate relatively near the road surface so that low barriers that are aesthetically acceptable and less costly can be used. The source height must be taken into account and given some special attention in a balanced noise-reduction scheme.

Given below are the components of exhaust system noise for 1 bank of a Detroit diesel 8V71 engine on an International truck with full load at 2,100 rpm with the microphone at 50 ft (15 m).

Noise Source	dBA
Muffler shell	72
Discharge	80.4
Pipe and leak	78.6
Overall exhaust system	83.0

Figure 14 shows the sound level measured during the SAE maximum acceleration test as the vehicle passed by the microphone with all sources silent except the standard exhaust system. The peak sound level is 86 dBA and relates to the figures above since the V-8 engine has dual exhaust or a doubling of the components. Figure 14 also shows the sound level of the same truck after dual 10×15 oval mufflers with exhaust stack silencers were installed. Just past the closest point of the microphone, the sound level of the exhaust system peaks to 69 dBA, some 16 dB lower than the standard installation.

Figure 15 shows the oval muffler, which was used in tests in the transportation department project to reduce the exhaust noise level. This is a change from a straight-through muffler to a double-rack system with a 10×15 oval configuration. The flow is diverted twice through resonator chambers. In addition, stack silencers are used at the pipe terminants.

Truck Cooling-System Noise

American trucks have been productive in large measure because of efficient cooling systems. The fan must move large volumes of air through the radiator to achieve the cooling. The typical cooling fan is a stamped sheet-metal, riveted subassembly, driven by a belt directly coupled to the engine. Until recently, little attention has been given to the noise of the cooling system.

Sound generated by fans varies principally with tip speeds, as shown in Figure 16. Decreasing fan tip speeds by increasing the number of blades and reducing rotational velocity or diameter are the directions to proceed in reducing fan noise. Aerodynamic shaping of fan blades and closer shrouding of tips are other ways to reduce fan noise level. Separating the fan from the engine block and removing obstacles in the fan air stream also have to be considered in fan noise reduction. Much more research is required to understand fan noise.

Figure 17 shows the increases in cooling, air flow, and noise when fan-to-radiator distances are increased. Each of these parameters reaches a maximum at some point and decreases beyond that point. The parameters do not necessarily reach their maximum values at the same point, but most important the cooling increases at a greater rate than air flow does because of the better distribution of air across the core. Optimum fan-to-radiator distance on the tests conducted in this program range

Figure 15. Oval muffler.

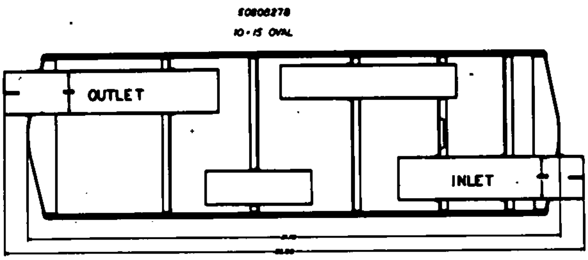


Figure 16. Effect of speed on fan noise.

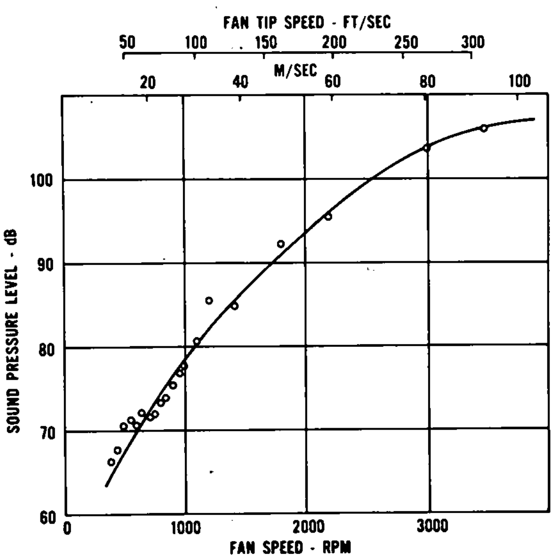


Figure 17. Effect of fan-to-radiator distance.

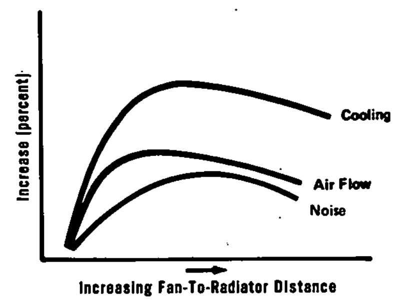


Figure 18. Shroud shape and transition.

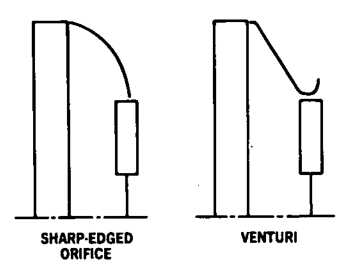


Figure 19. Diffusers for fan discharge.

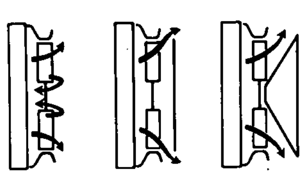
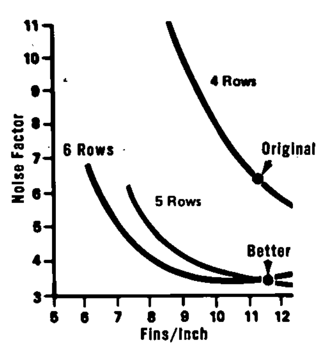


Figure 20. Noise factor for various radiator arrangements.



from 4 to 8 in. (10 to 20 cm). Noise reduction is achieved by optimizing cooling and fan-to-radiator clearance. The shroud shape and the fan position within the shroud are then considered.

The original shroud found on most trucks today most closely resembles the sharp-edged orifices shown on the left in Figure 18. The shroud shown on the right offers significant increases in performance and reduction in fan noise by reducing tip speed while maintaining constant cooling.

Previous research has indicated that a disk diffuser placed at the proper location behind the fan, as shown in the center of Figure 19, increases the air flow and reduces the horsepower (wattage) requirements of the fan. The effects appear to be a reduction in the recirculation losses near the fan hub, as shown in Figure 19 on the left. Improved designs take on the appearance of a mixed-flow fan, that is, one that combines axial and radial discharge. Theory indicates that a mixed-flow design has the best efficiency for the flow rates and pressure differences normally experienced in truck applications. This is particularly important in the design of engine or engine enclosures to produce quiet trucks. Such noise-reduction items block the nominal radiator air-flow passages and indicate the desirability of diverting the flow to seek discharge passages under the wheel wells or under the engine.

One final area of investigation involves the radiator itself. Figure 20 shows the noise factor for various radiator core arrangements. Noise factor is proportional to total air flow through the radiator times the square of the pressure; that is proportional to the general cooling system noise. The abscissa is the number of fins per inch, and the data are plotted on the basis of equal heat rejection from the radiator. If we compare the original design point, for the 4-row radiator, to the better points for 5- and 6-row radiators, we can see that the noise factor, or air flow times pressure squared, is reduced significantly. Thus, the air flow times pressure squared across the radiator is translated into reduction requirements for the fan so that the fan can be made smaller or made to turn slower. This is the area where the noise reduction is achieved.

A new trend in diesel truck design is toward increased radiator size and thermostatically controlled fans that rotate only a small portion of the time as needed and thus greatly reduce overall vehicle noise. The advanced design practices noted above that will lead to lower fan noise generation must be applied, nevertheless, to abate this source of noise during the periods of fan operation.

These combinations in new technology can immediately alter present production vehicles to achieve levels of approximately 81 dBA at 50 ft (15 m) under maximum acceleration conditions. This was indicated earlier in Figure 11. However, more stringent requirements have already been scheduled in various states and cities, and the Noise Control Act of 1972 adds pressure for still further reductions in truck noise levels in order that trucks may indeed approach the sound levels typical of automobiles. A more difficult goal of 75 dBA is proposed by the U.S. Department of Transportation. To achieve such a reduced sound level will require progressive application of the existing technology in the exhaust, intake, and fan areas.

Truck Engine Noise

Research in Great Britain, supported by several American engine manufacturers, indicates that future engine designs may indeed provide lower inherent mechanical and combustion noise levels. Until this new technology can be incorporated in engine designs, an alternative approach must be taken.

Figure 21 shows a concept of such an alternative approach to fundamental engine redesign; it is engine and transmission encapsulation and is noted by the heavy lines around the engine. Consideration has to be given to apertures for air discharge so that the engine is cooled. These apertures are also used for noise discharge. The maintainability of encapsulated engines is an important feature, and innovative mechanical design will be required to achieve acceptance by the trucking industry. Within the truck noise demonstration program of the U.S. Department of Transportation, truck

Figure 21. Engine-transmission enclosure.

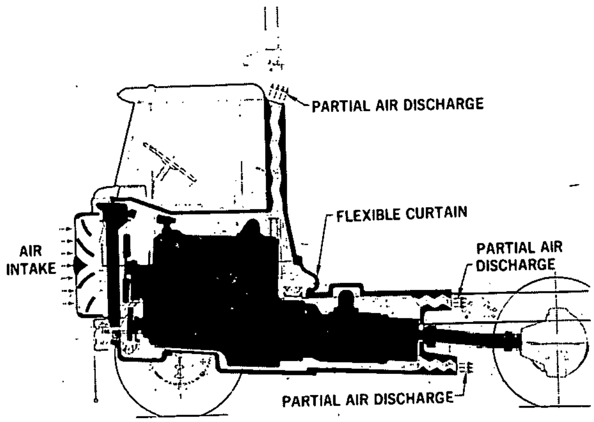


Figure 22. Diesel truck pull-away and highway noise.

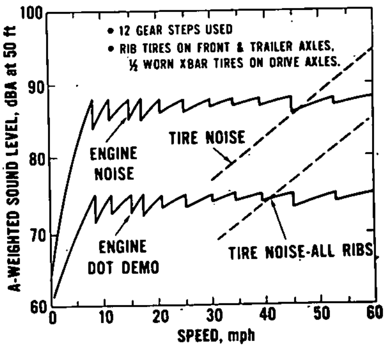
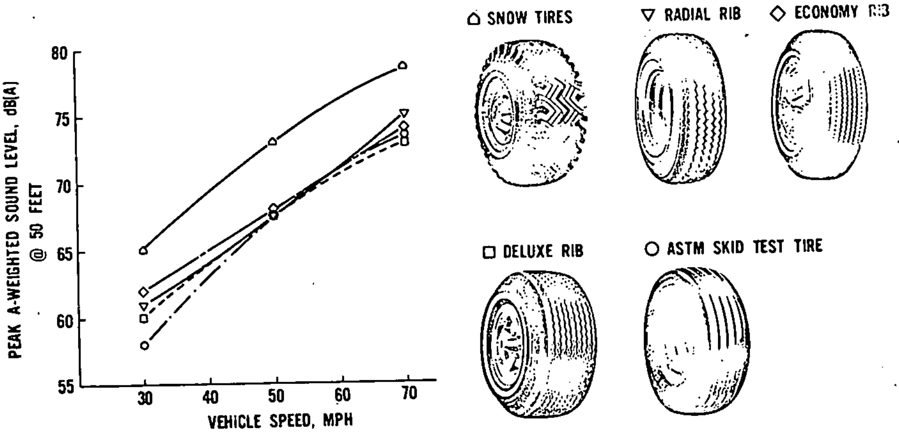


Figure 23. Passenger-car tire noise.



manufacturers have been looking at inspection panel damping, soft engine mounting, and other ways to reduce engine combustion and mechanical noise. A final option is encapsulation of the type shown in Figure 21. These manufacturers have taken on the challenging task of reducing overall vehicle noise levels to 75 dBA and have explored the practicality of whole engine and transmission enclosures as potential means to reduce the general mechanical clatter of an engine to levels required to achieve that goal.

Figure 22 shows what happens today when a heavy-duty diesel truck pulls away from a stop and accelerates to highway speeds. The engine noise shown as the jagged line indicates that the engine operates within several hundred rpm of its governed speed, and most of the vehicle speed control is maintained through the selection of appropriate gear steps during the acceleration. This tire noise becomes dominant at about 45 mph (72 km/h) and exceeds the engine noise level from speeds above 45 mph. If, as an option, the half-worn cross-bar tires are removed from the axles of the tractor and replaced with new rib tires, the noise would not be dominant until speeds exceed 60 mph (96 km/h).

If the goals of the noise-reduction demonstration project of the U.S. Department of Transportation are achieved, the engine noise levels will have been reduced substantially, as shown by the lower jagged line in Figure 22. Tire noise then is the dominant source at quite low speeds. Application of new-truck engine noise technology forces a significant requirement on the tire manufacturers to evolve technological solutions to bring tire noise levels into line with engine noise levels.

PASSENGER-CAR NOISE

In 1970, the U.S. Department of Transportation sponsored a pilot measurement program of passenger-car tire noise levels on a new section of Interstate 95 north of Washington, D.C. A 4-door sedan and a variety of test tires were used, and coast-by noise measurements were made with the engine shut off and transmission in neutral. The results of this experiment are shown in Figure 23. The quietest commercial tire, which has no sipes and only 4 circumferential grooves, is the ASTM skid test tire. The sound level produced by the skid test tire was slightly lower at 30 mph (48 km/h) but merged with the sound levels of deluxe rib, economy rib, and radial tires at higher speeds. Typical snow tires mounted on the rear axle and ASTM tires on the front of the same sedan, however, increased the sound level 5 dBA. These tires in this project were new and, if the trends established in the truck tire tests carry over to the passenger-car tires, sound levels will tend to increase as the tires are worn. The noisy snow tires were still below the sound level generated by more than 80 percent of the trucks at freeway speeds in the California survey.

MOTORCYCLE NOISE

Motorcycle noise, as shown in Figure 3, falls generally between automobile and truck noise. Not much information exists on motorcycle noise levels, but it is clear that exhaust noise is a dominant feature of motorcycles, followed closely by intake, engine, and chain noise. Noise levels for motorcycles, sports cars, and passenger cars shown in Figure 24 generally agree with those found on a much broader sampling by the California Highway Patrol but also indicate the general lack of exhaust muffling in the low-frequency range that accounts for the throaty roar of motorcycles. A similar low-frequency dominance is seen for sports cars.

Figure 25 shows still another investigator's findings of the broad range of noise levels emanating from motorcycles. Subsource contributions of component sources of motorcycle noise for the limited number of bikes tested are also shown. Exhaust noise exceeds the intake contribution, engine mechanical noise is a close third, and tire noise level is the least contributor because of the light loading on the tires.

One of the major problems with motorcycles is the "love affair" that the drivers seem to have with the sound of power. The sound of power can be enhanced by

Figure 24. Range of octave band noise levels at 25 ft (8 m) for passenger cars, sports cars, and motorcycles at 65 mph (105 km/h).

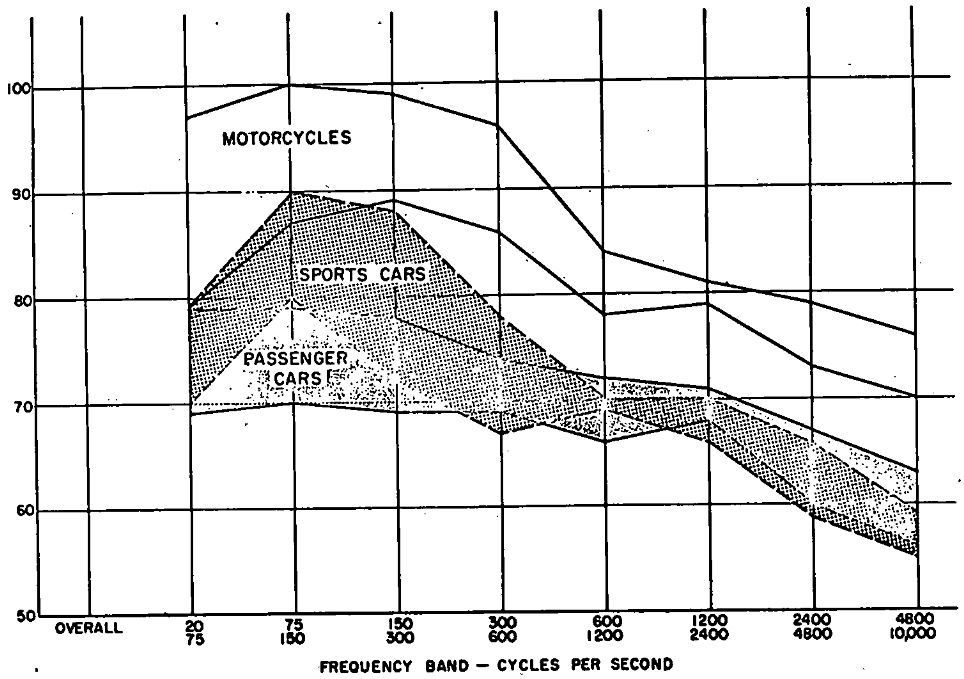
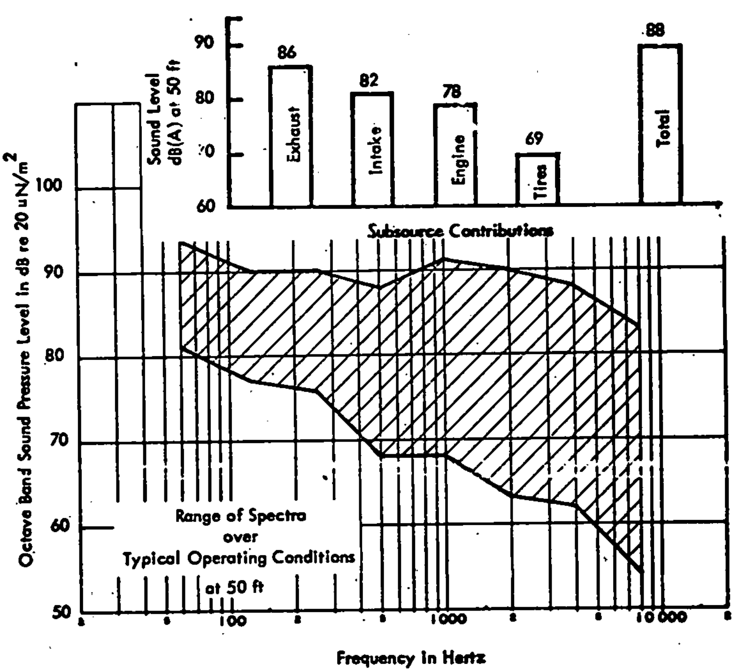


Figure 25. Motorcycle noise levels.



modifying the muffler, as shown in Figure 26. The noise level measured under maximum acceleration conditions for a variety of motorcycles is plotted as a function of engine displacement in cubic inches. The lower line indicates the general trend with standard production mufflers, which many cyclists prefer. These tests were performed by the Ontario Ministry of Transportation and Communications in 1967 (5). The specific test procedures were the International Standards Organization recommendation 362, which prescribes a sideline measurement distance of 25 ft (8 m). The measured data have been extrapolated to an equivalent 50-ft (15-m) sideline level for consistency with the other vehicle sound levels. For motorcycles, the approximate difference in 25- and 50-ft levels is 6 dB as shown on the shifted ordinate.

Figure 26 shows that the smaller bikes are considerably quieter than the largest U.S.-manufactured motorcycles. With modified exhaust systems, however, the smaller bikes can produce high sound levels. Further reduction of exhaust noise from motorcycles is possible; however, intake and engine noise is close to the noise levels emanating from standard exhaust mufflers. The application of engine enclosures for these small air-cooled engines presents a number of problems not encountered with the water-cooled automobile and truck engines. Notwithstanding these problems, industry members of the President's National Industrial Pollution Control Council suggested that the present voluntary maximum noise level standards of industry for bikes with engines greater than 240-cm^3 displacement could be reduced as follows (6):

Year	Feet	dBA
1971	50	92
1973	50	90
1978	50	86
1983	50	77

Comparable recommended maximum sound levels for bikes under 240 cm^3 displacement are 2 to 3 dB lower.

NOISE CERTIFICATION LEVELS

Table 4 gives a summary of California's new code for motor vehicle noise certification levels. It contrasts the motorcycle manufacturer's suggested achievable goals and the levels expected by regulatory agencies. Trucks are certificated for maximum vehicle noise equal to or less than 86 dBA measured at 50 ft (15 m) to the side of the centerline of the vehicle path. On January 1, 1975, this level dropped to 83 dBA and will drop to 70 dBA by January 1, 1988. Automobiles are certificated at levels only 2 dBA lower than those for the trucks. This surprisingly small difference illustrates the problem of automobile certification noise levels relative to operational noise levels.

SOUND PROPAGATION

Figure 27 shows how sound propagates away from a single vehicle. For simplicity, we assume that the noise is generated at the center of this source and that it is a point source. At relatively short distances away, this approximation is reasonable. The hemispheric nature of the propagation then dictates that the sound level is reduced by 6 dB for each doubling of distance away from the source. That is to say, a measurement of 90 dB at 50 ft (15 m) to the side of a passing vehicle would be 84 dB at 100 ft (30 m) to the side of that same passing vehicle.

Figure 27 also shows the way sound is propagated from an array of sources such as 2 trucks or many trucks and automobiles. In this case, the spreading is not hemispherical but hemicylindrical. The geometry dictates that, for each doubling of distance away from the source, the sound level will be reduced by 3 dB.

Figure 26. Maximum noise levels of motorcycles in acceleration test.

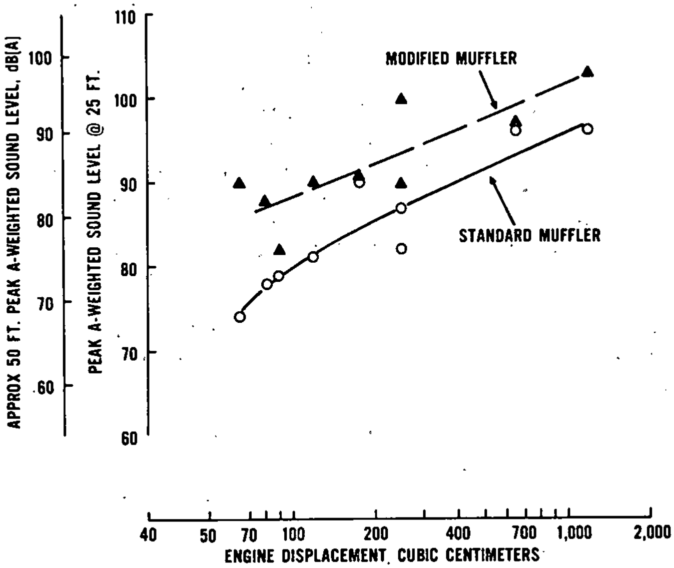
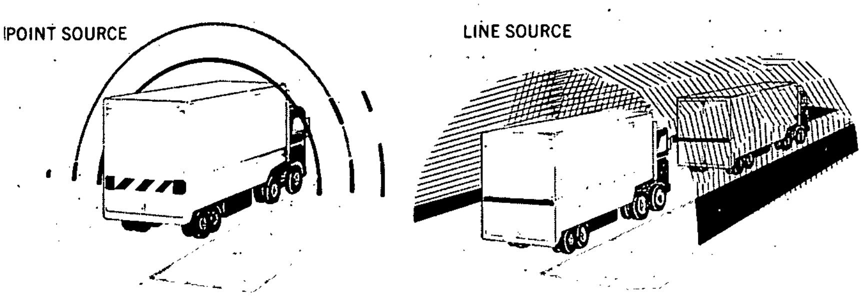


Table 4. California motor vehicle noise certification levels at 50 ft (15 m).

Vehicle	Noise (dBA) by Date of Manufacture 1967 to 1973	1972 to 1975	1974 to 1978	1977 to 1988	1987
Trucks	88	86	83	80	70
Automobiles	86	84	80	75	70
Motorcycles	88	86	80	75	70
Snowmobiles		82[a]			

[a]Enforcement agency and means not specified.

Figure 27. Sound propagation.



Of course, other things are to be considered in the propagation of sound either with point source or line source. One of the things that cause problems in predicting noise levels is the ground cover adjacent to highways, which will tend to attenuate the sound by 2 to 3 dB. However, one should not count on vegetation, even dense rows of bushes and trees, to provide much more than 2 to 3 dB unless broad areas of dense growth are present.

ATMOSPHERIC ATTENUATION

At significant distances away from the highway, substantial high-frequency content of the sound will be attenuated because of the absorption of the atmosphere. The high frequencies are attenuated as much as 30 dB/1,000 ft (300 m) over the predominant low frequencies of highway noise, which are barely affected by this phenomenon. Atmospheric attenuation is a function of temperature and humidity. Winds and temperature gradients can cause refraction of sound or curving of the sound rays, which will cause either reinforcement or reduction of noise.

TRAFFIC NOISE

Figure 28 shows one procedure for predicting the sound level emanating from a busy highway. Estimated is the sound level exceeded 50 percent of the time at a point 100 ft (30 m) from the side of the highway. The lowest line is the sound level generated by automobiles only traveling at 50 mph (80 km/h). As the percentage of trucks is increased in the traffic, the sound level increases. For example, if there are 100 vehicles per mile of roadway, automobiles alone would generate a median sound level of 69 dBA at 100 ft (30 m). Increasing the percentage of trucks from 0 to 20 percent raises the sound level from 69 to 75 dBA. This amounts to quadrupling the number of automobile sound sources if addition is on a simple energy basis, i.e., 20 trucks equals 320 automobiles or 1 truck equals 16 automobiles.

Another way to look at this is to consider a constant sound level of 69 dBA and ascertain what relative reduction in vehicle density is required as the number of trucks is increased. In this case we start with 100 vehicles per mile of roadway at 69 dBA. For passenger cars only and with 20 percent trucks, we have 69 dBA with 20 vehicles per mile of roadway. This comparison leads one to say that 4 trucks (20 percent of 20 vehicles per mile of roadway) plus 16 automobiles generates the same noise level as 100 automobiles.

HIGHWAY NOISE BARRIERS

Placing noise barriers along highways is another method for reducing vehicular traffic noise levels. Such barriers can be effective in reducing highway noise, and the higher the barrier the better (Table 5). The data do not fully indicate the direct relation between noise barriers and vehicle (especially truck) noise reduction. Noise emanates from trucks from several locations—exhaust stack, engine enclosure (casing radiation, cooling fan), and tires. Table 6 gives the complementary relation between barriers and truck noise reduction. If a typical truck is modified for quiet operation so that the exhaust noise is reduced by 15 dB and the engine noise by 10 dB, the total noise level at 100 ft (30 m) becomes 76.5 dBA, a reduction of 5.5 dB. Instead of quieting the truck, assume that an 8-ft (2.4-m) barrier is erected 25 ft (7.6 m) from the edge of the roadway. This barrier provides little noise reduction for the 12-ft (3.6-m) high exhaust noise, but substantial reductions for the engine and tire noises. The resultant noise level at 100 ft (30 m) is 78.5 dBA, a reduction of 3.5 dB. Now assume that both actions are taken together: The truck is quieted, and an 8-ft (2.4-m) barrier is erected. The resultant noise level at 100 ft (30 m) is 67 dBA, a total reduction of 15 dB.

Figure 28. Mean noise level estimates of mixed traffic.

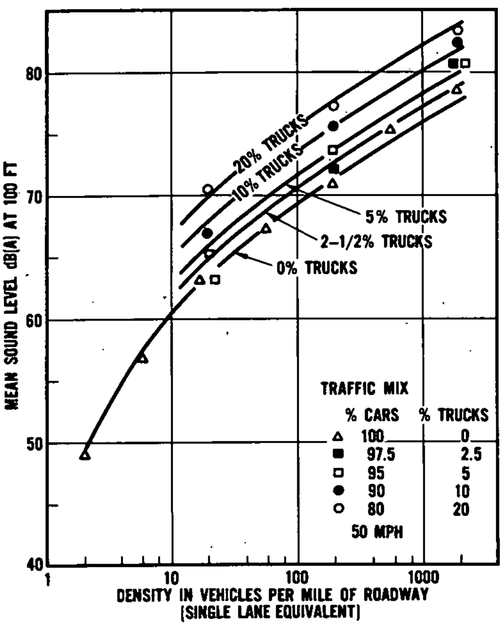


Table 5. Effect of noise-abatement measures on highway noise.

Number of Lanes	Noise Abatement Measure	Noise (dBA) by Distance From Edge: 100 ft (30 m)	125 ft (38 m)	200 ft (60 m)	300 ft (90 m)	400 ft (1200 m)
6	None	78	77	74	71	69
	Landscaping, 100 ft	73	72	69	66	64
	Barrier, 6 ft	67	66	64	61	58
	Barrier, 12 ft	63	62	60	56	54
	Depressed roadway, 10 ft	73	72	69	64	61
8	None	80	79	75	72	70
	Landscaping, 100 ft	75	74	70	67	65
	Barrier, 6 ft	70	69	66	63	51
	Barrier, 12 ft	65	65	64	61	55
	Depressed roadway, 10 ft	75	74	68	65	62

Note: Traffic consists of 11,000 vehicles per hour and includes 5 percent trucks. Speeds are 53 mph (85 km/h).

Table 6. Relation of quieting truck and using roadside barriers to reduce truck noise.

Truck-Barrier Combination	dBA at 50 ft (15 m): Exhaust[a]	Engine[b]	Tires[c]	Total dBA at 100 ft (30 m)
Typical truck	86	81	82	82
Typical truck quieted	71	71	82	76.5
Typical truck and 8-ft (2.4-m) barrier[d]	84	82	80	78.5
Typical truck quieted and 8-ft (2.4-m) barrier	69	62	70	67
Typical truck and 12-ft (3.6-m) barrier[d]	81	69	68	75.5
Typical truck quieted and 12-ft (3.6-m) barrier	66	59	68	64.5

[a]At a height of 12 ft (4 m) above roadway.
[b]At a height of 5 ft (1.5 m) above roadway.
[c]At roadway.
[d]At 25 ft (7.6 m) from edge of roadway.

Noise reduction in the vehicle will not by itself sufficiently reduce noise along highways and streets. Effective use of rights-of-way and land use controls along rights-of-way must also be undertaken.

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