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DOI:

[10.1016/S1470-2045\(12\)70280-2](https://doi.org/10.1016/S1470-2045(12)70280-2)

*Document Version*

Peer reviewed version

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*Citation for published version (APA):*

Benbrahim-Tallaa, L., Baan, R. A., Grosse, Y., Lauby-Secretan, B., El Ghissassi, F., Bouvard, V., ... International Agency for Research on Cancer Monograph Working Group (2012). Carcinogenicity of diesel-engine and gasoline-engine exhausts and some nitroarenes. *The Lancet Oncology*, 13(7), 663-664. 10.1016/S1470-2045(12)70280-2

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1  
2 **Carcinogenicity of diesel and gasoline engine exhausts and some nitroarenes**

3 Lamia Benbrahim-Tallaa, Robert A Baan, Yann Grosse, Béatrice Lauby-Secretan,  
4 Fatiha El Ghissassi, Véronique Bouvard, Neela Guha, Dana Loomis, Kurt Straif, on behalf of the  
5 International Agency for Research on Cancer Monograph Working Group  
6 International Agency for Research on Cancer, Lyon, France  
7

8           In June 2012, 24 experts from seven countries met at the International Agency for  
9 Research on Cancer (IARC) in Lyon, France, to assess the carcinogenicity of diesel and gasoline  
10 engine exhausts, and of some nitroarenes. These assessments will be published as Volume 105 of  
11 the IARC Monographs (1).

12           Diesel and gasoline engines are internal combustion engines that are the major power  
13 sources used in on-road vehicles worldwide. Diesel engines are also used for non-road transport  
14 (e.g. trains, ships) and (heavy) equipment in various industrial sectors (e.g. mining, construction)  
15 and in electricity generators, particularly in developing countries. Gasoline engines are also used  
16 for hand held equipment (e.g. chain saws).

17           Emissions from these engines are complex with varying composition. The gas phase  
18 consists of carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), and volatile organic compounds such  
19 as benzene and formaldehyde. Particles consist of elemental and organic carbon (EC, OC), ash,  
20 sulfate, and metals. Polycyclic aromatic hydrocarbons (PAHs) and nitroarenes are primarily  
21 present in the particle-phase, but some are also found in the gas phase. The qualitative and  
22 quantitative composition of the exhausts depends on the fuel, the type and age of the engine, the  
23 state of its tuning and maintenance, the emission control system, and the pattern of use. Diesel  
24 engine exhaust from engines with no or limited emission controls contains more particulate  
25 matter (2).

26           Over the last two decades, progressively tighter emission standards for on-road vehicles,  
27 introduced in North America, Europe and elsewhere, have triggered advances in diesel  
28 technology that resulted in lower emission of particulate matter, NO<sub>x</sub> and hydrocarbons.  
29 Emission standards in non-road applications are lagging and therefore these are still largely  
30 uncontrolled today. Moreover, in many less developed countries standards are not in place for  
31 both on-road and non-road use of diesel and gasoline engines.

1           The most influential epidemiological studies assessing cancer risks associated with diesel  
2 engine exhausts investigated occupational exposure among non-metal miners, railroad workers,  
3 and workers in the trucking industry.

4           The US miners study included a cohort analysis (3) and a nested case-control analysis that  
5 was adjusted for tobacco smoking (4). Both showed positive trends in lung cancer risk with  
6 increasing exposure to diesel exhaust, as quantified via estimated EC as a proxy of exposure.  
7 Trends were statistically significant in the nested case-control study, with a 2-3 fold increased  
8 risk in the highest categories of cumulative or average exposure. This study provides some of the  
9 strongest evidence of an association between exposure to diesel engine exhaust and lung cancer  
10 since there were few potential confounding exposures in these underground mines, and high  
11 diesel exposures were well-documented in current surveys.

12           In another US study a 40% increased risk for lung cancer was observed in railroad  
13 workers exposed to diesel exhaust compared to low and non-exposed (95% CI 1.30–1.51) (5).  
14 Indirect adjustment for smoking suggested that differences in smoking could not have influenced  
15 this excess risk substantially. This study was later extended by estimating diesel exposure based  
16 on work history and the history of dieselization of different railroads and found a significantly  
17 increased risk for exposed workers in the order of 70-80%; risk increased with greater duration of  
18 exposure but not with cumulative exposure (6).

19           A large cohort study in the US trucking industry reported an increased lung cancer risk of the  
20 order of 15-40% among drivers and dockworkers with regular exposure to diesel exhaust  
21 (7). There was a significant trend of increasing risks with longer duration of employment, with 20  
22 years of employment showing an approximate doubling of the risk after adjusting for tobacco  
23 smoking. When this study was extended with an exposure assessment involving contemporary  
24 measurements and exposure reconstruction based on EC, positive trends were observed for  
25 cumulative but not average exposure. These trends were markedly more pronounced when  
26 adjustment for duration of work was included in the models (8).

27           The findings of these cohort studies were supported by studies in other occupational groups  
28 and by case-control studies including various occupations involving exposure to diesel engine  
29 exhaust. A positive exposure-response relationship was found in several of these studies from the  
30 Europe and the USA, many of which were adjusted for tobacco smoking. Most notably, a pooled  
31 analysis of 11 population-based case-control studies from Europe and Canada showed a smoking-

1 adjusted increased risk for lung cancer after exposure to diesel engine exhaust, which was  
2 assessed by a job exposure matrix, and a positive dose-response in terms of both a cumulative  
3 exposure index and duration of exposure (9). Taken together these epidemiological studies  
4 support a causal association between exposure to diesel engine exhaust and lung cancer. An  
5 increased risk for bladder cancer was also noted in many but not all of the available case-control  
6 studies. However, such risks were not observed in the cohort studies.

7 The working group concluded that there was “sufficient evidence” in humans for the  
8 carcinogenicity of diesel engine exhaust.

9 The diesel engine exhausts and their extracts used in carcinogenicity studies with experimental  
10 animals were generated from fuels and diesel engines produced before the year 2000. The  
11 studies were considered by type of exposure: whole diesel engine exhaust; gas-phase diesel  
12 engine exhaust (with particles removed); and extracts of diesel engine exhaust particles. Whole  
13 diesel engine exhaust caused an increased incidence of lung tumours in rats (10). Diesel engine  
14 exhaust particles instilled intratracheally caused benign and malignant lung tumours in rats (11),  
15 and the particle extracts also caused lung carcinomas in rats and sarcomas at the injection site in  
16 mice (12,13). Gas-phase diesel engine exhaust did not increase the incidence of respiratory  
17 tumours in any of the species tested. The Working Group concluded that there was “sufficient  
18 evidence” in experimental animals for the carcinogenicity of whole diesel engine exhaust, of  
19 diesel engine exhaust particles and of extracts of diesel engine exhaust particles.

20 Diesel-engine exhaust, diesel-exhaust particles, diesel-exhaust condensates, and organic  
21 solvent extracts of diesel engine exhaust particles induced, in vitro and in vivo, various forms of  
22 DNA damage including bulky adducts, oxidative damage, strand breaks, unscheduled synthesis,  
23 mutations, sister chromatid exchange, and morphological cell transformation in mammalian cells,  
24 and also mutations in bacteria (14). Increased expression of genes involved in xenobiotic  
25 metabolism, oxidative stress, inflammation, anti-oxidant response, apoptosis and cell cycle in  
26 mammalian cells was observed.

27 Positive genotoxicity biomarkers of exposure and effect were also observed among humans  
28 exposed to diesel engine exhaust. The Working Group concluded that there is “strong evidence”  
29 for the ability of whole diesel engine exhaust to induce cancer in humans through genotoxicity.

1 Gasoline exhaust and cancer risk was only investigated in a few epidemiological studies and,  
2 because of the difficulty to separate the effect of diesel and gasoline exhaust in these studies, the  
3 evidence for carcinogenicity was evaluated as “inadequate”.

4 The Working Group considered the animal carcinogenicity studies on gasoline engine exhaust by  
5 type of exposure: whole gasoline engine exhaust; gas-phase gasoline engine exhaust (with  
6 particles removed) and extracts of gasoline engine exhaust condensate. Organic extracts of  
7 gasoline engine exhaust condensate induced a significant increase in lung carcinomas and  
8 papillomas of the skin in mice (15). In rats, the gasoline exhaust condensate induced a significant  
9 increase in carcinomas and sarcomas of the lung (16).

10 The Working Group concluded that there was “sufficient evidence” in experimental animals for  
11 the carcinogenicity of condensates of gasoline engine exhaust.

12 Gasoline engine exhaust induced chromosomal damage in mice, and changes in gene  
13 expression in rat lung that involved pathways related to xenobiotic metabolism and inflammation.  
14 In mammalian cells gasoline-exhaust particles and organic extracts of gasoline particles induce  
15 DNA adducts, DNA strand breaks, oxidative DNA damage, chromosomal aberrations, and  
16 morphological cell transformation, as well as gene mutations in bacteria. In mammalian cells,  
17 extracts of gasoline-engine particles altered expression of genes involved in inflammation,  
18 xenobiotic metabolism, tumour progression, and cell cycle. The gaseous phase of gasoline-engine  
19 exhaust was mutagenic to bacteria (17). The Working Group concluded that there is “strong  
20 evidence” for a genotoxic mechanism for the carcinogenicity of organic solvent extracts of  
21 particles from gasoline engine exhaust.

22 In conclusion, the Working Group classified diesel engine exhaust as “carcinogenic to  
23 humans” (Group 1) and gasoline engine exhaust as “possibly carcinogenic to humans” (Group  
24 2B).

25 Evaluations for ten nitroarenes, all of which have been detected in diesel engine exhaust, are  
26 shown in Table 1. Biomonitoring studies have shown that workers and the general population are  
27 exposed to these substances (18); (19); (20). All the nitroarenes were genotoxic to various extents  
28 in different assays. The Working Group reaffirmed the Group 2B classification of seven of these  
29 nitroarenes. Strong evidence for genotoxicity led to an upgrade of 3-nitrobenzanthrone to Group  
30 2B and similar findings in human cells led to an upgrade for 1-nitropyrene and 6-nitrochrysene to  
31 Group 2A.

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1 **Table 1: Evaluation of the nitroarenes**  
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4 <b>Agent</b>	5 <b>Evidence of carcinogenicity in experimental animals</b>	6 <b>Mechanistic evidence</b>	7 <b>Overall evaluation</b>
8 3,7-Dinitrofluoranthene	Sufficient	Weak	2B
9 3,9-Dinitrofluoranthene	Sufficient	Weak	2B
10 1,3-Dinitropyrene	Sufficient	Weak	2B
11 1,6-Dinitropyrene	Sufficient	Moderate	2B
12 1,8-Dinitropyrene	Sufficient	Moderate	2B
13 3-Nitrobenzanthrone	Limited	Strong	2B*
14 6-Nitrochrysene	Sufficient	Strong	2A*
15 2-Nitrofluorene	Sufficient	Weak	2B
16 1-Nitropyrene	Sufficient	Strong	2A*
17 4-Nitropyrene	Sufficient	Moderate	2B

18 \*Strong mechanistic evidence contributed to the overall evaluation (see text).  
19