

**ENVIRONMENTAL IMPACT ANALYSIS: GAS VS.
DIESEL IN LIGHT-DUTY HIGHWAY
APPLICATIONS IN THE U.S.**

LOREN CARL MARZ - Certified Consulting Meteorologist

October 2007

Revised May 2012

INTRODUCTION

Much has been written recently about the relative merits and disadvantages of pursuing a strategy of using diesel engines in light-duty, personal-use vehicles like cars, SUVs, and light-duty pickup trucks in North America. Most articles point out the fuel savings advantage of diesel engines when compared to equivalent gasoline engines in these applications, while usually mentioning the downside of “higher emissions” of NO_x (oxides of nitrogen) and PM (particulate matter). They generally fail to mention, however, that diesel engines tend to have, and have historically had, *lower* emissions of two other regulated criteria emissions – NMHC (non-methane hydrocarbons) and CO (carbon monoxide). Many state outright, or at least imply, that a significant market penetration of light-duty diesels will degrade air quality.

Many media reports on air pollution will invariably show images of diesel trucks “spewing” out large clouds of black smoke from their exhaust pipes. However, are diesels really more “polluting” than gas engines? Will a market penetration similar to what has occurred in Europe (~50%) degrade the air quality in the U.S.? This document will analyze in detail the relative environmental impacts of diesel vs. gasoline in light-duty applications.

PARTICULATE MATTER (PM) EMISSIONS

Light-duty diesel vehicles have historically tended to have higher mass emissions of PM than their gasoline engine equivalents, especially as measured during the official drive cycle in the U.S. – the FTP75 drive cycle. Diesel particulate matter (DPM) is suspected of both chronic (long term – like cancer) and acute (short term - like asthma attacks) health effects.

The U.S. Environmental Protection Agency (EPA) has classified DPM as a “likely” carcinogen, but has declined to classify it as a *known* carcinogen. As a matter of fact, EPA acknowledges that the overall evidence was weak to moderate, and that a **zero** risk couldn’t be ruled out.¹

Many organizations have run with the studies which show a positive correlation with DPM and cancer (and apparently ignored the studies which show a negative correlation), and have published estimates of the number of cancer cases that can be attributed to DPM. However, according to the U.S. Department of Energy:

“...these conclusions are based on the **flawed** MATES II study conducted by the South Coast Air Quality Management District (SCAQMD) in Southern California. (3) The MATES II study **arbitrarily** assigned 70% of the cumulative risk from air toxics to diesel particulate matter (PM) emissions. To support this conclusion, SCAQMD used elemental carbon as a surrogate for diesel PM. Although the EPA has used a similar approach to estimate levels of diesel PM in its Hazardous Air Pollutant Exposure Model (HAPEM), the agency acknowledges that this approach raises issues of the use of a gas-phase surrogate species for a particulate compound and that CO and PM emissions from mobile sources are not always correlated. Because SCAQMD did not

directly measure diesel PM, it calculated diesel PM in the ambient air from assumptions based on data nearly 20 years old.

Even if these factors were reasonably accurate, SCAQMD left unaccounted 67% of the residual particulate carbon captured at air monitoring stations for PM_{2.5}. This begs the question of what other sources contribute to the PM_{2.5} collected at the air monitoring stations. For example, the NFRAQS work indicated that **light-duty gasoline vehicles contributed about 60%** of the PM_{2.5} carbon measured at urban Denver sites and that these contributions were **2.5-3.0 times those from diesel**. This fraction closely matches the unaccounted residual particulate carbon from the SCAQMD PM_{2.5} air monitoring sites.

A more fundamental problem is that CARB's Scientific Review Panel also used the flawed MATES II study as the basis for its calculation that 410 out of a million Californians could get lung cancer from diesel exhaust PM. STAPPA compounded this error by simply taking the CARB estimates and extrapolating them across the country to predict 125,000 extra cases of cancer from diesel exhaust. (6) In turn, this calculation was used to support CARB's recommendation for the California Environmental Protection Agency to list diesel exhaust as a toxic air contaminant. CARB took this course despite being warned by the authors of a key railroad study that their work did not prove that diesel exhaust causes cancer...^{2, 3} (Emphasis added)

Another caveat with PM is that the particle sizes (aerodynamic diameter) vary dramatically across the PM emission spectrum – several orders of magnitude. PM emissions are currently regulated by mass, but many studies have shown that while gasoline engines typically have low mass PM emissions, they have particle *number* emissions equaling or even exceeding their diesel counterparts under some common driving conditions, and that their particle size distribution is significantly smaller than the particle size distribution of DPM.^{4, 5, 6} Very small particles have virtually no mass but may still be a significant health concern.

According to other studies:

"...Most of the particles added by the on-road fleet were below 50 nm in diameter....

...The higher the speed, the greater the particle concentration, and the smaller the particle size. This is a reasonable finding because at high vehicular speeds, particulate number emissions, **especially from SI engines**, increase with increased engine load, exhaust temperatures and exhaust flow...."⁷ (emphasis added)

"...Group average fuel-specific number emissions range from 3.9×10^{14} to 1.0×10^{17} particles/kg of fuel...

...SI engines emit a higher proportion of smaller particles than do diesels..."⁸

“...Petrol engine particulates are composed of much smaller particles than those from diesel engines. In some reports, the petrol engine particles were found practically entirely in the **nanoparticle** range (<50 nm)....

...The [petrol] particle number emissions increase significantly at rich air-to-fuel ratios. At such conditions, comparable particle numbers may be emitted from petrol and diesel engines...⁷⁹

Another issue that needs to be taken into account is the relative toxicity of gas and diesel PM. According to studies conducted by the U.S. Centers for Disease Control (CDC), PM from gasoline engines tends to be more toxic per unit mass⁹, especially at colder ambient temperatures.¹⁰

Several other studies suggest that DPM from newer engines may have less health impacts than earlier engine studies may have suggested. For example, underground miners are typically exposed to levels of DPM that are much higher than even the worst ambient levels, but generally have no higher incidences of lung cancer than would be normally expected in the general population.¹¹

Furthermore, all light-duty (and heavy-duty) diesel vehicles sold since January 2007 have been equipped with diesel particulate filters (DPF). DPF has been shown to be very effective in virtually eliminating DPM with respect to both mass and numbers, in many cases to levels at or below ambient levels.^{12, 13} A recent very comprehensive study of exhaust from a DPF-equipped diesel truck engine by the Health Effects Institute (HEI) has found no evidence of gene-damaging effects in the animals studied, and only a few mild effects on the lungs due to high NO₂ exposures.⁸³

Even the California Air Resources Board (CARB) has acknowledge that light-duty diesel vehicles fitted with DPF have *lower* levels of PM emissions (mass) than even modern gasoline vehicles^{14, 80} and this was supported by other studies.^{15, 16} Testing by EPA of its “Clean Diesel Combustion” technology has also shown sub-milligram level of PM mass emission in the FTP75 drive cycle when using a DPF.¹⁷

Furthermore, there is evidence that DPM is not a significant contributor to ambient PM_{2.5} (particles with an aerodynamic diameter of 2.5 μm or less). According to EPA, national exposure modeling using their HAPEM-MS3 model suggests that in 1996, annual average DPM exposure from on-road DE sources in urban areas was 0.8 μg/m³, whereas in rural areas, exposures were 0.4 μg/m³. A RfC (reference concentration) of 5 μg DPM/m³ is a chronic exposure likely to be without an appreciable risk of adverse human health effects.¹⁸ For reference, the current National Ambient Air Quality Standard (NAAQS) for PM_{2.5} is 15 μg/m³, meaning that the contribution of DPM to ambient PM_{2.5} is only about 5% or less in typical non-attainment urban areas. This predates ultra-low sulfur diesel (ULSD) fuel and the new ultra-low emission diesel vehicles currently in production. A source apportionment study conducted by the University of Tennessee estimates that DPM from ALL diesel sources – on-road and off-road – in large cities in the southeastern CONUS (e.g., Atlanta) accounts for fewer than 1 μg/m³, which is less than 4 percent of the ambient PM_{2.5} in those cities.⁵² Another source apportionment study suggests that diesel exhaust

contributed about 2% of the ambient PM_{2.5} mass in Washington, D.C., while GASOLINE exhaust contributed 21%, based on 718 PM_{2.5} samples taken between 1988 and 1997.⁶⁸

A review of several other source apportionment studies concluded that GASOLINE vehicles are generally responsible for the majority of mobile source PM emissions in the U.S.⁶⁹ A 2012 study by researchers from Environment Canada has found that “black carbon” (BC or “soot”) emissions from light-duty gasoline vehicles are at least a factor of 2 higher than previous North American measurements, and a factor of 9 higher than currently used emission inventories in Canada.⁸⁵

DPM is expected to drop precipitously as older, high emitting diesels are replaced by new, very low emission diesels and/or DPFs are retrofitted on trucks in the current fleet. EPA estimates the PM_{2.5} contribution from “highway diesel” sources will drop from 110,000 tons/year in 2001 to about 10,000 tons/year by 2030, while PM_{2.5} emissions from “highway non-diesel” sources will *increase* from 50,000 tons/year in 2001 to nearly 57,000 tons/year by 2030.¹

Nonattainment with the PM_{2.5} NAAQS is not as widespread as nonattainment with the ozone NAAQS, but nevertheless, is an issue for mainly large metropolitan areas.⁴⁴

One last consideration that needs to be taken into account with respect to sources of ambient PM_{2.5} is secondary PM production by gaseous precursors. It is becoming increasingly apparent that secondary PM generally makes up a significantly larger portion of ambient PM_{2.5} than does primary (directly emitted) PM. Among emissions from light-duty vehicles, NO_x, hydrocarbon (HC) emissions and volatile organic compounds (VOC) produce indirect (secondary) PM_{2.5}.

PM nitrate contributes to ambient PM_{2.5} levels, but its production has been shown to be highly non-linear²² or even have an inverse relationship (i.e., reducing ambient NO_x levels actually causes PM nitrate levels to increase).²³ Also, PM nitrate is inorganic and soluble in water, and is relatively larger than most other secondary PM_{2.5}.²⁴ Thus it would not be expected to contribute to health issues as significantly as carbonaceous PM_{2.5}.

On the other hand, secondary PM_{2.5} produced by the oxidation of VOC (or secondary organic aerosols – SOA) tends to contribute to a significant portion of overall ambient PM_{2.5}.^{25, 26} It also tends to be very small – in the nucleation and/or accumulation modes – meaning SOA is generally made up of nanoparticles (aerodynamic diameter <50 nm) and/or ultrafine particles (aerodynamic diameter <100 nm).²⁷ Gasoline vehicles are **by far** the largest anthropogenic contributors to the hydrocarbon inventories.^{28, 29}

Generally, SOA is formed by hydrocarbons comprised of six or more carbon atoms.³⁰ Raw gasoline vapor (from the evaporation of gasoline) is a large source of these hydrocarbons, since it is a mix of hydrocarbons generally consisting of six or more carbon atoms. The following is an exercise to illustrate the potential contribution to the PM_{2.5} inventory of HC/VOC emissions:

Based on EPA emission factors⁵⁴, diesel fuel produces about 1/6 the VOC emissions of gasoline in

the “well-to-pump” (WTP) phase of life-cycle emissions. “Conventional Gasoline” produces about 5.70 grams of VOC per gallon WTP, while “Low Sulfur Diesel” produces about 0.95 grams of VOC per gallon WTP, using DOE default BTU/gallon values for gasoline (116,090 BTU/gal) and low sulfur diesel fuel (129,488 BTU/gal). According to EIA⁷¹, 8,736,000 barrels/day, or about 367 million gallons/day of gasoline are consumed in the U.S. Assuming most of this consumption is by motor vehicles, that's about 134,000,000,000 gallons of gasoline consumed by the U.S. vehicle fleet per year. 134,000,000,000 gallons X 5.70 g/gal = ~842,000 tons of VOC WTP per year from the fuel gasoline.

An equivalent amount of diesel fuel consumed, even neglecting the typically lower fuel consumption of diesel vehicles, would be 134,000,000,000 gallons X 0.95 g/gal = 140,000 tons of VOC produced. 842,000 tons – 140,000 tons = >700,000 tons difference.

Using a conservative SOA yield of 4% (for gasoline HC emissions)²⁷, ~28,000 additional tons of SOA would potentially be produced indirectly (secondary PM), which in itself significantly exceeds the EPA estimated 10,000 tons from “highway diesel” sources in 2030.¹

SOA can account for up to 90% of organic aerosol mass in urban areas²⁷, organic aerosol typically makes up the largest mass fraction of PM_{2.5}^{26,41}, and GASOLINE exhaust and GASOLINE vapor account for ~80 percent of ambient NMHC in on-road samples and at regional air monitoring locations in SoCAB.^{29,66} Thus it would seem prudent to focus more on this source of PM.

As noted, NOx can produce PM_{2.5} (PM nitrate). However, PM nitrate is not calculated here for several reasons:

Production of PM nitrate has been shown to be highly non-linear with respect to ambient NOx concentrations.

PM nitrate is generally relatively coarse (>1 μm diameter) compared to other secondary PM.²⁴

PM nitrate is inorganic and generally highly soluble in water, meaning PM nitrate would be easily diluted and cleared from the respiratory system compared to relatively insoluble carbonaceous PM (e.g., SOA, EC).

Just the switch to ultra-low sulfur diesel (ULSD) fuel in the U.S. reduced primary PM mass emissions from diesel engines by 10% according to EPA.⁵³ Reductions of the smallest particles (nanoparticles) by a factor of at least four have been reported.²¹

As previously discussed, according to EPA, by 2030, PM_{2.5} mass emissions from “highway diesel” will fall to about 10,000 tons/year (from about 110,000 tons in 2001) just from emission controls currently in place. “Highway non-diesel” PM_{2.5} emissions will rise from about 50,000 tons/year in 2001 to almost 57,000 tons/year in 2030. This does not include SOA production from evaporative

emissions. So direct (primary) PM_{2.5} mass emissions from gasoline will be almost six times as much as from diesel highway sources in spite of the fact that only about 3.4 times as much gasoline is consumed on-highway in the U.S. compared to diesel fuel.³¹

Also, at least 840,000 tons of gasoline will still be wasted through this evaporation process. That is roughly 276,000,000 gallons of gasoline (@ 6.1 pounds/gallon) that are simply wasted (and as outlined, significantly contribute to air pollution).

Hypothetically switching the entire light-duty fleet to diesel would save almost 236,000,000 gallons of fuel per year (276,000,000 gallons – 40,000,000 gallons), not counting the superior fuel mileage of diesel vehicles.

Switching just 33% of the light-duty vehicle fleet in the U.S. to diesel could reduce WTP VOC emissions to $(0.67 \times 134,000,000,000 \text{ gallons} \times 5.70 \text{ g/gal}) + (0.33 \times 134,000,000,000 \text{ gallons} \times 0.95 \text{ g/gal}) = 610,400 \text{ tons/year}$. $842,000 \text{ tons/year} - 610,400 \text{ tons/year} = 231,600 \text{ tons/year}$ or almost 76,000,000 gallons of gasoline/year not evaporated as VOC. Again, this does not take into account the typically much lower fuel consumption of diesel vehicles, so even assuming gasoline technology that achieves roughly the same fuel mileage as diesel technology (e.g., gasoline-hybrid technology), 76,000,000 gallons of gasoline/year would not only not be wasted, but would not contribute to ozone formation in VOC-limited areas nor contribute to the production of ~9300 tons/year of SOA (i.e., almost as much PM_{2.5} as EPA expects from the entire “highway diesel” fleet per year in 2030).

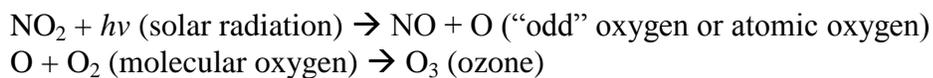
Finally, a 2012 study has shown that exhaust from gasoline vehicles contributes more to the production of SOA than exhaust from diesel vehicles.⁸⁴

OZONE PRECURSOR EMISSIONS

Oxides of nitrogen ($\text{NO}_x = \text{NO} + \text{NO}_2$), volatile organic compounds (VOC), and carbon monoxide (CO) are all considered “ozone precursors”. Ozone, the main component of “smog”, is not emitted directly from motor vehicles but is formed secondarily in the atmosphere from reactions of these ozone precursors in the presence of sunlight (solar radiation).

Diesel engines generally produce more NO_x , while gasoline engines generally produce more VOC (called NMHC or NMOG as direct emissions from vehicles) and CO. Gasoline vehicles also are responsible for far more evaporative VOC emissions (gasoline vapor) as a result of the highly volatile fuel that they use (gasoline or gasoline/ethanol blends).

Many reports on ground-level ozone or “smog” formation typically use the adjective “smog-forming” when describing NO_x . However, this is quite misleading since NO_x can also be “smog-destroying” in many common conditions (NO_x reacts directly with ozone). NO_x (actually NO_2) is required for the formation of ozone since it is the source of “odd” oxygen in the atmosphere:

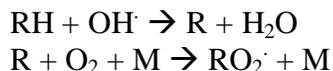
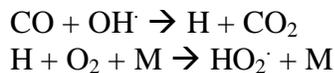


However, the NO that is produced from the photo-dissociation of NO_2 is available to immediately react with O_3 :



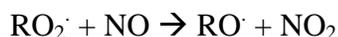
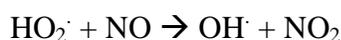
And the cycle starts all over again. Thus, this little pseudo-equilibrium (NO_x photolytic cycle) does not produce net ozone and NO_x in and of itself cannot account for ozone accumulation in the atmosphere. This is where VOC and CO enter the picture.

VOC and CO emissions are oxidized in the atmosphere mainly by the hydroxyl radical ($\text{OH}\cdot$):



(M is a non-participating molecule which carries off excess energy – e.g. N₂)

HO₂· and RO₂· (peroxy radicals) are capable of oxidizing NO to NO₂ and thus compete with O₃ in this process:



Without as much NO to consume the O₃, the O₃ can accumulate.

When ambient levels of VOC are very high relative to ambient NO_x levels (more than about 8:1), the VOC oxidation products consume enough NO that the only limiting factor in O₃ formation is the amount of NO_x in the atmosphere. Under this condition, ozone formation is “NO_x-limited”.

When ambient levels of VOC are low (or at least not very high) relative to ambient NO_x levels (less than about 8:1), there is enough ambient NO around to react with (consume) some of the O₃ and preclude high ambient levels of ozone. Under this condition, ozone formation is “VOC-limited”.

Studies by the U.S. Department of Energy, National Renewable Energy Lab (NREL), of the “weekend effect”, have empirically shown that all large urban areas studied thus far are “VOC-limited” with respect to ozone formation.^{32, 33} The “weekend effect” is a phenomenon that’s been observed for several decades, especially in the Southern California Air Basin (SoCAB), where ambient ozone levels tend to be much higher on weekends in spite of significantly lower ozone precursor emissions (especially NO_x).

EPA has acknowledged this phenomenon.^{34, 35, 76, 77, 78}

The U.S. National Oceanic and Atmospheric Administration (NOAA) also suggests that focusing on NO_x emissions may not have the desired impact on ambient ozone reductions.^{47, 49}

Low rain water pH (i.e., acid rain) does not correlate well with nitrate ion concentration in the rain water (r² = 0.4). Correlation is much better with sulfate ion concentration (r² = 0.8).⁵¹

Highway diesel vehicles will continue to be a lesser source of NO_x emissions than gasoline vehicles, according to EPA.¹ By 2030, NO_x emissions from "highway diesel" will fall to about 261,000 tons/year (from about 3,750,000 tons in 2001) just from the emission controls currently in place. "Highway non-diesel" NO_x will fall from about 4,320,000 tons/year in 2001 to about 1,290,000 tons/year in 2030. But that means that "highway non-diesel" sources will contribute five times more NO_x emissions than "highway diesel" sources.

Carbon monoxide (CO) is not only an ozone precursor, it is also an acutely toxic substance for which a NAAQS has been established. No area in the U.S. is in non-attainment with the NO₂ NAAQS⁵⁵, but there are areas of the Southwestern CONUS that are still in "serious" non-attainment (defined as value ("Design Value") of 16.5 ppm and above⁵⁶) with the CO NAAQS.⁵⁷ NAAQS values for criteria pollutants are available on the EPA web site (<http://www.epa.gov/air/criteria.html>).⁵⁸ CO is not as reactive as typical VOCs (CO also produces peroxy radicals when it is oxidized to CO₂ in the atmosphere), but the relative CO emissions are growing compared to HC/VOC emissions, and thus ambient levels of CO are growing relative to HC/VOC levels. At least 20% of urban ozone and as much as 50% can be attributed to CO emissions.^{59, 60} Nearly all CO emissions in urban areas come from the exhaust of **GASOLINE** vehicles.^{61, 62}

Interestingly, very little has been done with highway CO emissions from a regulatory perspective since 1981.^{63, 64, 65} Thus, a new vehicle can be sold in all 50 states in the U.S. that may have emissions of CO essentially as high as a vehicle sold in 1981. Even though uncontrolled CO emissions have been reduced greatly by the modern catalytic converter, the relative reduction still trails NO_x emission reductions mandated by Tier 2/LEV II.

TOXIC AIR EMISSIONS

According to several sources, diesel is typically much lower in air toxic emissions (currently unregulated) than gasoline as primary engine emissions^{6, 16, 36}, emissions from the fuel, and secondary formation of air toxics from precursor emissions.

These include such toxic substances as acrolein, benzene, formaldehyde, and 1,3-butadiene.

In addition to the production of SOA, the atmospheric decomposition (oxidation) of hydrocarbon vapors results in the secondary formation of formaldehyde (HCHO), a potential carcinogen, and stable intermediate of the hydrocarbon decomposition/oxidation process.⁴⁸

Raw gasoline vapors are a source of air toxics by themselves (BTEX = benzene, toluene, ethylbenzene, xylene).⁷⁴ Based on EPA emission factors⁵⁴, "Conventional Gasoline" produces about 0.017 grams (17 mg) of benzene per gallon WTP, while "Low Sulfur Diesel" produces about 0.008 grams (8 mg) of benzene per gallon WTP, using DOE default BTU/gallon values for gasoline (116,090 BTU/gal) and low sulfur diesel fuel (129,488 BTU/gal). 134,000,000,000 gallons/year X 0.017 g/gal = ~2500 tons of VOC WTP per year from the fuel gasoline. This in addition to higher exhaust emissions of benzene result in far higher "well-to-wheels" emissions of benzene for gasoline-fueled vehicles.

GREENHOUSE GASES EMISSIONS

Due to their significantly higher fuel economy (typically 25% - 55% depending on driving cycle), diesel vehicles have substantially lower carbon dioxide (CO₂) emissions than equivalent gasoline vehicles, in spite of the fact that diesel fuel has somewhat more carbon content than gasoline (about 14% more).⁷²

According to EPA, diesel engines also tend to have far lower emissions of other greenhouse gases such as methane (CH₄) and nitrous oxide (N₂O).^{37, 67}

It takes more energy to refine gasoline than it does diesel fuel, about twice as much depending on grade of crude oil (0.055 to 0.120 BTUs-process-energy (including electricity) per BTU-ULSD; 0.102 to 0.208 BTUs-process-energy/BTU-gasoline (with ultra-low sulfur); average of 0.0812 BTU/BTU ULSD produced vs. 0.170 BTU/BTU RFG produced).³⁸ Thus CO₂ emissions are also about twice as much from the production of the fuel.

According to a report⁸¹ released by Toyota Motor Corporation...

WTT GHG emissions @ “future” gasoline...

12.19 g CO₂e/MJ (gasoline); 7.88 g CO₂e/MJ (ULSD)

121.89 MJ/gal (gasoline); 134.38 MJ/gal (diesel)

12.19 g CO₂e/MJ – 7.88 g CO₂/MJ = 4.31 g CO₂e/MJ more for gasoline

12.19 g/MJ X 121.89 MJ/gal = 1485.8 g CO₂e/gal (gasoline)

7.88 g CO₂e/MJ X 134.38 MJ/gal = 1058.9 g CO₂e/gal (ULSD)

1485.8 – 1058.9 = **426.9 g more CO₂e/gal for gasoline**

According to the Massachusetts Institute of Technology (MIT)⁸²...

Fuel Cycle GHG emissions...

4.9 g C/MJ (gasoline); 3.3 g/MJ (ULSD) → 17.97 g CO₂e/MJ (gasoline); 12.1 g CO₂e/MJ (diesel)

121.89 MJ/gal (gasoline); 134.38 MJ/gal (diesel)

17.97 g CO₂e/MJ X 121.89 MJ/gal = 2190.36 g CO₂e/gal (gasoline)

12.1 g CO₂/MJ X 134.38 MJ/Gal = 1626 g CO₂e/gal (diesel)

2190 – 1626 = **564 g more CO₂e/gal for gasoline**

The higher GHG emissions in the fuel production cycle at least partially offsets the higher carbon content of diesel fuel.

CONCLUSIONS

The current generation of light-duty diesel vehicles sold in the U.S. is lower than equivalent gasoline vehicles in virtually all emissions except NO_x, and that's being addressed to a significant degree (Bin 5/LEV II diesel vehicles being introduced; 0.05 grams NO_x/mile at 50,000 miles; 0.07 grams/mile at 120,000 miles FUL). This will result in significantly less NO_x emissions produced by diesel vehicles than gasoline vehicles, even on a per-unit-volume-of-fuel-consumed basis (and diesel vehicles typically can go significantly farther per unit volume of fuel consumed) when taking into account the higher NO_x emissions of gasoline in the WTP phase of the life-cycle emissions.

Gasoline vehicles typically have higher emissions of hydrocarbons (both direct and indirect), CO, and now even PM_{2.5}, all currently regulated. Gasoline vehicles typically have higher emissions (direct and indirect) of unregulated air toxics like benzene.

Nonattainment with the 8-hour ozone NAAQS (National Ambient Air Quality Standards) is still quite widespread, especially in/near large metropolitan areas. Ozone precursor emissions from gasoline vehicles (both direct and indirect) have been shown to be the primary culprits in ground-level ozone production in these areas.

Nonattainment with the PM_{2.5} NAAQS is less widespread, but nevertheless, is an issue for again mainly large metropolitan areas. Every year, primary and secondary emissions from GASOLINE vehicles are becoming a larger source of ambient PM, especially relative to diesel vehicles.

Nonattainment with the carbon monoxide (CO) NAAQS is isolated, but is still a "serious" problem for areas of the Southwestern CONUS. Gasoline vehicles are by far the largest source of CO in urban areas.

There are no areas of the U.S. that are still in nonattainment with the nitrogen dioxide (NO₂ – one of the oxides of nitrogen which are collectively referred to as "NO_x") NAAQS.

The DOE/NREL "weekend ozone effect" studies have shown that large decreases in NO_x emissions (along with smaller decreases in VOCs and CO emissions) often result in higher ambient ozone levels in urban areas.

A study by NOAA suggests that lowering ambient NO_x levels results in higher "ozone production efficiency" (OPE) of the NO_x; higher ambient NO_x levels result in lower OPE. These phenomena tend to offset each other; thus NO_x controls are ineffective for controlling ambient ozone levels.

From chemistry theory, NO_x alone will not result in net ozone production; VOC and CO oxidation in the atmosphere forms peroxy radicals which oxidize NO (nitric oxide – also a "NO_x") into NO₂ (the ozone precursor form of NO_x).

Most NO_x from diesel engines is in the form of NO (nitric oxide).

From chemistry fundamentals, NO destroys ozone:



Downwind ozone levels do not decrease linearly (i.e., do not decrease proportionately) to decreases in urban NO_x levels (plume).

PM nitrate is reduced by less than 3%; i.e., PM_{2.5} is not significantly influenced by increases or decreases in ambient NO_x levels.

Low rain water pH (acid rain) does not correlate well with nitrate ion concentration in the rain water ($r^2 = 0.4$). Correlation is much better with sulfate ion concentration ($r^2 = 0.8$).

Diesel sources do not appear to be significant contributors to ambient PM_{2.5} and will become even less significant as older, high-emitting diesel vehicles are replaced by current DPF-equipped diesel vehicles.

The atmospheric decomposition of hydrocarbon vapors results in a significant amount of organic PM (SOA) produced by evaporative VOC emissions from gasoline production, distribution, storage, and refueling.

The atmospheric decomposition of hydrocarbon vapors results in the formation of formaldehyde, a potential carcinogen and stable intermediate of the hydrocarbon decomposition/oxidation process.

In most cases, diesel engines produce far fewer greenhouse gas emissions than comparable gasoline engines and diesel fuel is less energy intensive to refine.

This Environmental Impact Analysis concludes that diesel vehicles produce a lower environmental impact than equivalent gasoline and gasoline-hybrid vehicles. As Bin 5/LEV II diesel vehicles are introduced in the U.S., the environmental impact of new diesel vehicles can be expected to be far less than equivalent gasoline vehicles.

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