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APPENDIX AVAILABLE ON REQUEST

Special Report 17

Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects

Chapter 2. Emissions from Motor Vehicles

HEI Panel on the Health Effects of Traffic-Related Air Pollution

Appendix D. Summary of Tunnel Studies in the Past Decade

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APPENDIX D. SUMMARY OF TUNNEL STUDIES IN THE PAST DECADE

Table D.1 Summary of Tunnel Studies in the Past Decade

Citation	Location (Year of data collection)	Parameters Measured	Emission Factors Reported	Key Findings
(Allen et al 2001)	Caldecott Tunnel, Orinda, CA (1997)	NH_3, PM of various sizes, OC, EC, sulfate, nitrite, 13 additional elements	Yes	Emissions composition for LDDV and HDDV are compared. Peak of size distribution for both types of vehicles was between 0.1-0.18 µm, but peak from HDDV was broader. PM mass emitted from LDV (largest component OC) was much smaller than that from HDDV (largest component EC). Ammonia emissions attributed to vehicles with three-way catalysts and operating under fuel rich conditions.
(Colberg et al 2005)	Lundby Tunnel, Gothenberg, Sweden; Plabutsch Tunnel, Graz, Austria; Gubrist tunnel, Zurich, Switzerland (2001, 2002)	NO_x, CO, total VOCs	Yes	Road gradient has a greater effect on HDV NO_x emissions than LDV NO_x emissions. For the Gubrist tunnel (previously studied) NO_x emission factor of LDV decreased by a factor of 3 from 1993 to 2002, while that of HDV decreased by 30%.
(De Fré et al 1994)	Craeybeckx Tunnel, Antwerp, Belgium (1991)	NO_x, SO_2, CO_2, CO, NMHC, VOCs, PAHs, Pb	Yes	NO_x emission factors were correlated with Flanders Emissions Inventory (EIVR) and CORINAIR model, while CO and HC emission factors were higher than the CORINAIR model but lower than EIVR inventory.
(Fraser et al 1998)	Van Nuys Tunnel, Los Angeles, CA (1993)	221 vapor-phase, semivolatile, and $PM_{2.5}$-phase organic compounds, $PM_{2.5}$ (and associated metals, ionic species, EC, and OC), CO, CO_2	Yes	Emission for CO, CO_2, and VOCs were higher than those measured in other tunnel studies. Fine PM emissions consist largely of carbonaceous material accompanied by significant amount of secondary ammonium nitrate. The atmosphere was enriched with certain gas-phase and PM-phase organic compounds thought to be produced by atmospheric chemical reactions. The contribution of resuspended soil dust was small.

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Citation	Location (Year of data collection)	Parameters Measured	Emission Factors Reported	Key Findings
(Gertler et al 2002)	Tuscarora Mountain Tunnel, PA (1999)	PM_{10} and $PM_{2.5}$ mass, UF PM number, elements, EC, OC	Yes	Emissions of $PM_{2.5}$ and most other species were substantially higher in HD than in LD vehicles. Compared to earlier measurements in the same tunnel (in 1992), $PM_{2.5}$ emissions decreased by 90% and NO_x/CO ratio increased by 48%. Both LD and HD vehicles emitted UF PM with a mean size of 17-33 nm; these were composed primarily of sulfur.
(Gillies et al 2001)	Sepulveda Tunnel, Los Angeles, CA (1996)	$PM_{2.5}$, PM_{10}, OC, EC, elements	Yes	PM_{10} and $PM_{2.5}$ contain significant amount of iron (15 and 5% respectively) attributed to resuspended road dust and engine and tire wear. PM_{10} emission factors were higher than those reported for newer cars and trucks and for similar vehicle ages from dynamometer tests. $PM_{2.5}$ emission factors correlated with NO_x emission factors because of the significant contribution from HD vehicles (even though they represented <3% of the fleet).
(Grieshop et al 2006)	Squirrel Hill Tunnel, Pittsburgh, PA (2002, 2004)	$PM_{2.5}$, CO, CO_2, NO_x, OC, EC, inorganic ions, metals	Yes	NOx, $PM_{2.5}$, EC, and OC emission rates were larger during morning period (truck-dominated). Emission rates of particulate metals from brake wear were highest during rush-hour while those of crustal elements (Fe, Ca, Mg, Li) and of Zn and Mn were highest during heavy truck traffic in early morning. OC/EC ratio was higher in the fall relative to the summer (attributed to in creased partitioning of OC in the gas-phase and changes in fuel composition. Emission rate for HDDV and LDV were estimated.

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Citation	Location (Year of data collection)	Parameters Measured	Emission Factors Reported	Key Findings
(He et al 2008)	Zhujiang Tunnel, Pearl River Delta, China (2004)	$PM_{2.5}$ and associated EC, OC, inorganic ions, trace elements, and speciated OC	Yes (fleet and HDV and LDV)	Based on comparison with other tunnel studies emissions of OC appeared to be less influenced by geographical areas and fuel composition than emissions of trace elements. HDV had a 5.1 times larger $PM_{2.5}$ mass emission rates, 8.7 times larger EC emission rates, and 4 times larger OC emission rates.
(Ho et al 2007)	Shing Mun Tunnel, Hong Kong (2003)	15 Carbonyls	Yes	Carbonyl emissions from diesel vehicles were seven times higher than those from non-diesel vehicles. Five carbonyls accounted for approximately 85% of the total emissions: formaldehyde, acetaldehyde, acetone, crotonaldehyde, and benzaldehyde for diesel-fueled vehicles; formaldehyde, acetone, methyl ethyl ketone, m,p-tolualdehyde, and acetaldehyde for non-diesel-fueled vehicles.
(Holmen et al 2001)	Caldecott Tunnel, Orinda, CA (1997)	PM	No	Continuous PM emissions were determined using Lidar (a laser detector). HD Trucks contribute 3 times more to the above road PM-lidar than cars, despite cars outnumbering trucks 20:1 on the road. This PM is most attributed primarily to resuspended road dust rather than primary PM emissions.
(Hwa et al 2002)	Taipei Tunnel, Taipei City, Taiwan Taipei (2000)	CO, NO_x, NHMC, VOCs	Yes	Results from the tunnel experiment were compared with USEPA Mobile 5b (M5b) and modified Mobile-Taiwan (MT2). M5b overpredicts NO_x, and NHMC emission while it underpredicted CO emissions. MT2 also underpredicted CO, but predicted NOx and NHMC fairly accurately. The most abundant VOCs (by volume) were ethene, acetylene, and toluene.

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(Indrehus and Vassbotn 2001)	Høyanger Tunnel, Gothenburg, Norway (1994 and 1995)	CO, NO_x, NO_2	No (tunnel concentrations)	Correlations between NO_2 and CO or NO were high. The NO_2/NO_x showed a curve that indicated increased formation of NO_2 at NO_x>2ppm during periods of low ventilation. Ventilation fan control based on CO measurement is not sufficiently reliable and should be supplemented to limit NO_2 concentration.
(Jamriska et al 2004)	Bus tunnel, Brisbane, Australia (bus fleet, 2000)	$PM_{2.5}$ mass, submicrometer PM number	Yes	Emission factors are in good agreement with those from dynamometer tests for the same bus fleet.
(Kristensson et al 2004)	Söderledstunnel, Stockholm, Sweden (1998-1999)	49 PAHs, CO, NO_x, BTX, Aldehydes, PM_{10}, $PM_{2.5}$ PM size distribution, EC, OC, PM	Yes	Emission factors for CO and benzene decreased by 15%, those of carbonyls by a factor of 2, and that of NO_x remained unchanged relative to measurements made in 1993.The majority of particles were distributed around 20nm in diameter. Gaseous emissions were found to be higher than in Switzerland and the US, due to lower catalytic converter use.
(Kurtenbach et al 2001)	Kiesbergtunnel, Wuppertal, Germany (1997-1998)	HONO, NO_2, NO, CO_2	Yes (fleet and single vehicle)	Emission factors for all species were well correlated with traffic density during daytime; HONO emission factor was higher than expected during night time (low traffic) due to heterogeneous formation from NO_2 on the tunnel walls, which depends on the air residence time. The HONO/NO_x ratios from the traffic fleet were in good agreement with those from single vehicle measurements.

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(Laschober et al 2004)	Kaisermühlen Tunnel, Vienna, Austria (2002)	PM, TC, BC, Zn, Cu, Pb, Ni, V, sulfate, ammonium	Yes	The PM emission factor was lower compared to those reported from other tunnels. Good correlation found between emission of TC and BC and amount of HDV present. From these data separate emission factors for HDV and LDV were derived. These were lower than published dynamometer results. The emission factor for ammonium was smaller than those reported for other tunnels (due to differences in car fleet age).
(Legreid et al 2007)	Gubrist Tunnel, Zurich, Switzerland (2004)	Oxygenated VOCs and NMVOCs	Yes (fleet and LDV and HDV)	The most abundant species emitted were ethanol, toluene, isopropanol, and acetaldehyde (formaldehyde was not measured). The emission factors were lower for all species that were measured in 2002 and 1993 in the same tunnel. OVOCs were mainly produced by HDV and NMHC by LDV.
(Ma et al 2004)	Buk-Ak Tunnel, Seoul, Korea (2000)	PM of different sizes, EC, OC, elements (by single particle analysis)	No	Carbonaceous compounds (OC and EC) were the most important contributor to particle mass. Particles were found to be internally mixed with soil-derived and vehicle- and engine-derived trace elements.
(Martins et al 2006)	Jânio Quadros Tunnel and Maria Maluf Tunnel, São Paulo, Brazil (2004)	CO, CO_2, NO_x, SO_2, VOCs	Yes	NO_x emissions were 14 times greater for the HD fleet than for the LD fleet, while CO emissions were only slightly higher. For the whole fleet, the most abundant VOCs were toluene and 1-butene; the most abundant aldehydes were acetaldehyde and formaldehyde.
(McGaughey et al 2004)	Washburn Tunnel, Houston, TX (2000)	CO, NO_x, NMOC	Yes	NO_x emissions were lower than previous tunnel studies pre-1996 while NMOC was slightly higher than previously reported.

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Citation	Location (Year of data collection)	Parameters Measured	Emission Factors Reported	Key Findings
(Oda et al 2001)	Kojouike Tunnel, Kurashiki City, Japan (1996-1997)	23 PAHs, 20 oxy-PAHs	No	The most abundant PAHs inn the air was pyrene, followed by fluoranthene; the most abundant oxy-PAH was anthraquinone. These were also the most abundant compounds in guardrail dust and soil. Most PAHs were from automobile exhaust
(Phuleria et al 2006)	Caldecott Tunnel, Orinda, CA (2004)	$PM_{2.5-0.18}$, $PM_{0.18}$, hopanes, total and individual PAHs, and EC in each PM fraction, CO, CO_2	Yes	Most organic species were an order of magnitude higher in the ultrafine mode than the fine mode in both LDV and HDV. Even though PAH emission factors from HDV were generally larger than those for LDV, LDV emissions were enriched in heavier PAHs (relative to total emitted mass or total PAH emissions); HDV emissions were enriched in lighter PAHs. Emissions of hopanes and steranes were one order of magnitude higher for HDV than for LDV.
(Rogak et al 1998)	Cassiar Connector, Vancouver, Canada (1993 and 1995)	CO, CO_2, NO_x, NHMC	Yes	Emission factors calculated for LD and HD vehicles, but focus was on LD. LD emission rates were similar to those measured in 1993 or reported in other studies with a few exceptions: lower CO/NOx emission ratios and a higher NOx emission rate relative to other tunnels. Emission rates agreed well with rates modeled using the MOBILE5 model.
(Schmid et al 2001)	Tauerntunnel, Austria (1988 and 1997)	CO_2, CO, NO_x, SO_2, PM_{10}, NMVOC, BTEX, aldehydes	Yes	Emissions of regulated pollutants derived from HDV while emissions of unregulated pollutants derived mainly from HDV. Emission factors for CO and NMHC declined by 90% and those of PM by 20-40% from 1988 to 1997 while emission rates of NOx increased slightly.

Table D.1 Summary of Tunnel Studies in the Past Decade

Citation	Location (Year of data collection)	Parameters Measured	Emission Factors Reported	Key Findings
(Stemmler et al 2005)	Gubrist Tunnel, Zurich, Switzerland (1993 and 2002)	14 C4-C8 VOCs (including BTEX)	Yes	Emission factors decreased by 80% over 9 years. Emission factors for benzene and toluene agreed with emission factors derived from emission inventories (based on dynamometer tests).
(Stemmler et al 2004)	Gubrist Tunnel, Zurich, Switzerland (2000)	CFC-12, HCFC-22, HFC-134a	Yes	Emissions of CFC-12 and HFC-134a attributed to losses from AC units of cars; emissions of HCFC-22 attributed to losses from refrigeration systems of trucks.
(Sternbeck et al 2002)	Tingstad Tunnel and Lundy Tunnel, Gothenberg, Sweden (1999-2000)	TSP, PM_{10}, and Cu, Zn, Cd, Sb, Ba, Pb (in TSP)	Yes	Emission factors for metals similar in two tunnels; those for TSP and PM_{10} differed widely due to differences in contribution of resuspension. Cd, Cu, Sb, Ba, Pb were predominantly from break wear rather than combustion.
(Zanini et al 2006)	Bologna, Italy (2001)	TSP, PM_9, $PM_{3.3}$, 12 PAHs daily concentrations	No	Experimental uncertainties limited the comparison of varying fuels types using single vehicle.

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