Diesel, cars, and public health.

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In September 2015, the United States Environmental Protection Agency (U.S. EPA) issued a notice of violation of the Clean Air Act to the automobile manufacturer Volkswagen.¹ It alleges that four-cylinder Volkswagen and Audi diesel vehicles from the years 2009-2015 included software that circumvented accurate emissions testing for certain air pollutants--in particular, nitrogen oxides (NO_x). The U.S. EPA and the California Air Resources Board determined that such vehicles emitted up to 40 times more NO_x than current emission standards allow. It is estimated that there are a total of 11 million affected vehicles worldwide.

The Volkswagen violation of the Clean Air Act represents not only a violation of air quality law, but also of public health due to the wide range of adverse health effects associated with exposure to NO_x and nitrogen dioxide (NO₂).^{2,3} A recent report on the impact of the Volkswagen violation estimated a total of 59 premature deaths in the U.S. due to excess emissions by affected vehicles.⁴ Motor vehicles represent the largest source of human exposure to NO₂.²

The mean population-weighted concentration of outdoor NO₂ in the U.S. was estimated to be 10.7 ppb based on a national land-use regression model for the year 2006.⁵ Worldwide, concentrations of NO₂ are increasing most rapidly in parts of Eastern Asia, Europe, North Africa, and the Middle East

and decreasing in North America and Oceania.⁶ Current NO₂ standards are 53 ppb (annual mean) and 100 ppb (98th percentile of 1-hour daily maximum concentrations averaged over three years) in the U.S. The World Health Organization air quality guideline value for NO₂ is 21 ppb (annual mean).^{2, 7}

Epidemiologic studies have reported consistent evidence that short-term exposure to NO₂, of several hours to days is associated with increases in all-cause mortality as well as a variety of respiratory and cardiovascular effects. A meta-analysis of 43 studies reported a 0.71% (95% confidence interval (CI) 0.43%-1.00%) increase in risk for all-cause mortality per 10 µg/m³ increase in 24h NO₂ concentrations.⁸ NO₂ has also been associated with a variety of adverse respiratory health effects, including airway irritation, respiratory symptoms, and in susceptible populations, such as those with asthma, an increase in emergency room visits and hospital admissions.^{9,10} Recent meta-analyses have also indicated a role of short-term NO₂ in risk of myocardial infarction,¹¹ heart failure,¹² and stroke.¹³

Long-term exposure to NO₂, of several months to years, has also been related with increases in all-cause and cause-specific mortality. A recent meta-analysis of 19 studies reported a 4% (95% CI 2-6%) increase in risk for total mortality per each 10 µg/m³ increase in NO₂ concentrations and a

13% (95% CI 9-18%) increase in risk for cardiovascular mortality which remained in multi-pollutant models adjusting for concentrations of particulate matter $<2.5\ \mu\text{m}$ in diameter ($\text{PM}_{2.5}$).¹⁴ There were also small positive associations observed with both total and cardiovascular mortality in multi-pollutant models adjusting for both $\text{PM}_{2.5}$ and ozone (O_3) concentrations in recent studies in California and Canada.^{15,16}

Long-term exposure to NO_2 has also consistently been associated with a range of adverse respiratory effects including increases in asthma incidence and severity in children and decrements in lung function.^{17,18} There was an inverse association between NO_2 and lung volume growth.¹⁹ NO_x was also associated with exhaled nitric oxide (FeNO), an indicator of airway inflammation, in the California Children's Health Study.²⁰ In adults, a positive association between NO_2 and incident adult wheeze was recently reported in the U.S. Sister Study.²¹ Another study noted associations between NO_2 and biomarkers of systemic inflammation in chronic obstructive pulmonary disease patients.²² There was a 3% (95% CI 2%-3%) increase in risk for respiratory mortality overall in a recent meta-analysis per each $10\ \mu\text{g}/\text{m}^3$ NO_2 .¹⁴

The International Agency for Research on Cancer also has classified both ambient air pollution and diesel engine exhaust as Group 1 human

carcinogens.^{3,23} A meta-analysis of 20 epidemiologic studies reported a 4% (95% CI 1-8%) increase in lung cancer risk per each 10 $\mu\text{g}/\text{m}^3$ increase in NO_2 concentrations.²⁴ Evidence for other cancer sites is still unclear.

Currently the U.S. EPA is updating the policy-relevant science related to the health effects of NO_2 in the review of the National Ambient Air Quality Standards (NAAQS).² It is also important to note that NO_x is an important contributor to the secondary formation of air pollutants including particulate matter (PM) and O_3 , both of which have also been independently associated with a range of adverse human health effects.²⁴⁻²⁸

There are a number of interventions available to address the Volkswagen violation specifically including stopping the sale and production of affected vehicles, repairing vehicles sold during this time period, and improving verification of vehicle emissions throughout the automobile industry.

Broader-scale interventions also include supporting the technological transition towards cleaner vehicles (natural gas, hydrogen, hybrid, and electric) to reduce in general emissions of NO_x and other particulate and gaseous air pollutants.^{29,30} It is important to note, however, that there are still non-exhaust emissions from brakes, tires, clutch, and road surface wear that contribute nearly half of the total particle emissions from vehicles.³¹

The chemical composition of these includes various heavy metals, sulfur,

organic compounds, elemental carbon, and PAHs, for example, which have also been associated with multiple adverse health effects.^{32,33}

Though such technological interventions towards cleaner vehicles will result in large reductions in air pollution emissions, it is important to consider that alone they do not address the underlying public reliance on private vehicles for transport, which is an important determinant of public and population health, with impacts on traffic incidents, physical inactivity, and social and health inequalities. There is now accumulating evidence of large health co-benefits of urban transport policies that act to promote the replacement of car trips by public transport and active mobility (i.e. walking, cycling), including improvements in levels of physical activity, and reductions in levels of air pollution, noise, and traffic incidents.³⁴ Table 1 provides a direct comparison of the potential impacts of technological transition vs. a city model of public transport and active mobility. It is important to note that the city model does not exclude technological transition but rather represents a more holistic view of urban planning intervention.

Possible urban planning interventions to promote public transport and active mobility are presented in Figure 1. Interventions include improvements to increase land-use mix, density, connectivity,

intermodality, greenspaces, public transport and active mobility infrastructure, traffic calming, accessibility, aesthetics, traffic safety, reduction of crime, economic incentives for public transport and active mobility and disincentives for vehicle use and parking.^{35,36}

Numerous studies have attempted to assess the impact of such urban planning interventions on rates of public transport use and active mobility. Improvements in cycling infrastructure, including increasing the number and quality of bike lanes, bike parking spaces, and traffic signals, resulted in two- to six-fold increases in cycling rates in a number of cities worldwide.^{37,38} Bike sharing systems have also been shown to further increase cycling rates in Europe.^{37,38} The implementation of rapid bus transit systems increased public transport use in several cities including Curitiba, Guangzhou, Jakarta, and Mexico City.³⁹ Reductions in vehicle use were also observed in London, Singapore, and Stockholm following the implementation of a congestion charge, and in Berlin with the low emission zone.³⁷

Clear public and population health benefits have been observed following the implementation of such urban planning interventions. Rates of walking and cycling were seen to increase directly through active mobility interventions, as well as indirectly through increases in the use of public

transport, with clear health benefits for multiple health outcomes.^{34,40,41}

Multiple health risk assessments have quantified estimated changes in physical activity levels through the substitution of car trips by public transport and active mobility, in terms of benefits for all-cause and cause-specific mortality, including cardiovascular disease, cancer, and other endpoints.^{34,42} A systematic review of 30 studies examining the impact of active transportation interventions estimated a median health benefit-risk or benefit-cost ratio of 9.³⁴

Other co-benefits of car substitution include the reduction of air pollution and noise emissions.³⁴ Although changes in physical activity levels only benefit travelers, reductions in air pollution and noise emissions benefit all city inhabitants.^{34,42} Car substitution is also associated with improvements in traffic safety, as public transport is one of the safest modes of urban transport.⁴³ Improvements in active mobility infrastructure and increased driver awareness regarding pedestrians and cyclists also play a role.⁴⁴

Further, the implementation of an urban mobility model promoting public transport and active mobility can also contribute to reduce levels of social and health inequalities in the population.^{45,46} Disadvantaged groups may be disproportionately exposed to local environments which discourage physical activity and activity mobility. They may also perceive their environment to

have greater levels of traffic, fewer opportunities for walking, and have concerns regarding crime and levels of personal safety.⁴⁷⁻⁴⁹ Higher rates of traffic-related injuries and death have also been noted among lower socioeconomic groups.⁴⁸ Enhanced public transport can improve mobility and access to services among the disadvantaged, as well as strengthen social relationships.⁴⁵

In conclusion, the recent Volkswagen violation provides a valuable opportunity not only to support the technological transition required to reduce emissions from motor vehicles directly, but also to reconsider our models of cities where both public transport and active mobility can contribute to healthier urban environments and populations. Such a transition requires a broader examination of urban planning and transport policies by relevant authorities, health practitioners, and citizens.

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Figure legend

Figure 1. Urban planning interventions to promote public transport and active mobility.

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Table. Potential impacts of technological transition vs. a city model of public transport and active mobility.

	Technological transition (Natural gas, hydrogen, hybrid, and electric cars)	City model (Public transport, active mobility)
Exhaust emissions (NO _x , PM, O ₃ , SO ₂)	X	X
Greenhouse gases (CO ₂)	X	X
Traffic noise	X	X
Non-exhaust emissions (PM [heavy metals, other chemicals])		X
Traffic incidents		X
Physical inactivity		X
Social inclusion and health inequalities		X