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Short communication

Valuing the human health damage caused by the fraud of Volkswagen☆

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ABSTRACT

Recently it became known that Volkswagen Group has been cheating with emission tests for diesel engines over the last six years, resulting in on-road emissions vastly exceeding legal standards for nitrogen oxides in Europe and the United States. Here, we provide an estimate of the public health consequences caused by this fraud. From 2009 to 2015, approximately nine million fraudulent Volkswagen cars, as sold in Europe and the US, emitted a cumulative amount of 526 ktonnes of nitrogen oxides more than was legally allowed. These fraudulent emissions are associated with 45 thousand disability-adjusted life years (DALYs) and a value of life lost of at least 39 billion US dollars, which is approximately 5.3 times larger than the 7.3 billion US dollars that Volkswagen Group has set aside to cover worldwide costs related to the diesel emissions scandal.

1. Introduction

Since 2009, Volkswagen Group has installed software in eleven million diesel engines to circumvent emission tests (Brooks, 2015; Volkswagen AG, 2015a, d). On the road, passenger cars equipped with these engines emit on average 0.9 g of nitrogen oxides (NO_x) per kilometre driven (Thompson et al., 2014). This is approximately 21 times the amount legally permitted in the USA (0.043 g/km) (US EPA, 2015c), and approximately 5–11 times the amount legally permitted in the European Union (0.18 g/km from 2009 to 2013; 0.08 g/km from 2014) (Delphi, 2015).

NO_x emissions form fine dust particles (PM2.5) in the atmosphere (Rao et al., 2012). After inhalation, these fine particles may cause or worsen respiratory disease, such as bronchitis and lung cancer, and can aggravate existing heart disease, leading to increased hospital admissions and premature death (Lelieveld et al., 2015; Pope et al., 2002; Tang et al., 2015). Increase in disability adjusted life years (DALYs) has been related to the emission of NO_x in different global geographical regions, based on changes in chronic mortality and respiratory disease-related morbidity (Tang et al., 2015). In addition to this physical measure of health damage, the value of statistical life (VSL) provides a monetary way to express health damage in terms of US dollars of value lost. The VSL represents the extent to which an individual would trade consumption of other goods and services for small changes in his or her own mortality risk, also known as willingness to pay (Hammitt, 2000). VSL has been used to quantify health impacts for cost-benefit analyses (Héroux et al., 2015). Here, we make an estimate of the human health damages resulting from the fraud by Volkswagen in Europe and the United States. We assess two scenarios, one in which the fraudulent cars are recalled and no additional NOx emissions will occur from 2016 onwards, and one in which the fraudulent cars will fully complete their service lives.

2. Material and methods

In total, 482 thousand fraudulent passenger cars were sold in the USA, and 8.5 million in European countries (Table 1). The latter number is the amount of fraudulent cars that could be accounted for based on publicly available sources. In the USA, fraudulent cars were allocated to a year of sale between 2009 and 2015 based on Volkswagen Group sales data of TDI Clean Diesel cars (Table 2). In that period, 494,294 TDI Clean Diesel cars were sold, which is close to the 482 thousand fraudulent passenger cars reported. European fraudulent cars were allocated to a year of sale between 2009 and 2015 based on total amounts of passenger cars delivered by Volkswagen Group to customers in the European Union (Table 2).

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Table 1
Numbers of fraudulent cars sold in USA and European Union.

Country	Number of fraudulent cars sold	Source
United States of America	482,000	US EPA (2015b)
European Union	8,474,693	
of which:		
Germany	2,800,000	Martin and Barkin (2015)
United Kingdom	1,189,906	Ruddick (2015)
France	946,092	Labbé (2015)
Spain	683,626	Sánchez (2015)
Italy	648,458	Flak (2015)
Belgium	393,648	Fioretti (2015)
Austria	363,400	Luxemburger Wort (2015)
Sweden	224,746	Magnusson (2015)
Netherlands	160,000	Back (2015)
Czech Republic	148,000	Lopatka and Vodstrcilova (2015)
Norway	147,139	Jacobson (2015)
Poland	140,000	Szary (2015)
Switzerland	128,802	Franklin (2015)
Romania	105,000	Ilie (2015)
Portugal	94,400	Tonkin and Massey (2015)
Denmark	91,000	Tange and Heavens (2015)
Ireland	79,348	McAleer (2015)
Slovakia	46,000	Botíková (2015)
Luxembourg	43,000	Luxemburger Wort (2015)
Finland	26,000	The Associated Press (2015)
Greece	9000	Tomlinson (2015)
Latvia	5087	LETA (2015)
Estonia	2041	Tambur (2015)

Table 2
Allocation of fraudulent cars to year of sale.

	Year of sale								
	2009	2010	2011	2012	2013	2014	2015	2009–2015	Source
United States of America									
Total number of cars sold by VW Group	213,454	256,830	324,402	438,133	407,704	366,970	238,074 [a]	2,245,567	(PR Newswire, 2011, 2012; Volkswagen of America Inc., 2013, 2014, 2015a,b,c,d,e, f,g,h,i)
Fraction of cars sold as TDI Clean Diesel	0.219[b]	0.220	0.216	0.206	0.235	0.216	0.223[c]	–	
Number of TDI Clean Diesel cars sold	46,661	56,503	70,071	90,255	95,823[d]	79,422[d]	55,559	494,294	
Normalised to 482,000 fraudulent cars	45,500	55,097	68,328	88,011	93,440	77,447	54,177	482,000	
European Union									
Total number of cars sold by VW Group[e]	3,208,000	3,173,807	3,448,874	3,040,173	3,046,507	3,266,530	2,028,000[f]	21,211,891	(Volkswagen AG, 2010, 2011, 2012, 2013, 2014, 2015b, c)
Normalised to 8,474,693 fraudulent cars	1,281,678	1,268,017	1,377,913	1,214,627	1,217,157	1,305,062	810,238	8,474,693	

[a] Sales data for months January–August.
[b] Average fraction of the years 2010–2014.
[c] Average fraction over the months April–August; used for the months January–May.
[d] Number of TDI Clean Diesel cars directly reported, thus not calculated from total number of cars sold and fraction TDI Clean Diesel cars thereof.
[e] Combined sales for Western, Central, and Eastern Europe, minus sales in Russia.
[f] Sales data for months January–June.

These data show that approximately 40% of passenger cars sold by Volkswagen Group in the European Union in the period 2009–2015 were fraudulent cars.

For every car sold in the USA, the yearly distance travelled was estimated for all years throughout its service life, based on data from the National Highway Traffic Safety Administration (NHTSA) (Lu, 2006). These yearly distances are corrected for vehicle age (the yearly distance travelled decreases over time), and the probability of survival (the probability for a car to still be in operation also decreases over time). For cars sold in Europe, the relationship between yearly distance travelled and vehicle age was derived from a study on Italian passenger cars (Caserini et al., 2013) (Table 3). Based on the distances travelled, NO_x emissions by fraudulent cars were estimated for every year from 2009 onwards, using the test data from Thompson et al. (2014). The difference was then calculated between actual NO_x emissions by fraudulent cars and the

Table 3
Average distance travelled per car in USA (Lu, 2006) and Europe (Caserini et al., 2013), depending on vehicle age.

Vehicle age (years)	Average distance travelled (km)[a]	
	USA	*EU*
1	22,673	22,166
2	22,088	20,460
3	21,406	18,824
4	20,621	17,258
5	19,736	15,763
6	18,754	14,337
7	17,689	12,982
8	16,555	11,697
9	15,376	10,482
10	14,169	9337
11	12,467	8263
12	10,264	7258
13	8216	6324
14	6421	5459
15	4924	4665
16	3718	3941
17	2775	3287
18	2051	2704
19	1506	2190
20	1101	1747
21	802	1374
22	582	1070
23	424	837
24	308	675
25	224	582
Full service life[b]	244,850	203,683

[a] The average distance at a specific vehicle age, accounting for the corresponding probability of survival.
[b] The maximum service life was assumed to be 25 years.

legal standards applicable to the cars in operation that year (Table 4).

Finally, health impacts were quantified corresponding to the estimated additional NO_x emissions (Table 5). This was done using the reported DALYs per unit of NO_x emission in Europe (90 DALY/ktonne), and in the USA (20 DALY/ktonne) without future discounting (Tang et al., 2015). Tang et al. (2015) used the global chemistry transport model MIROC-ESM-CHEM, which can calculate the global distributions of tropospheric aerosols and gas-phase species. They derived a change in the mass concentration of PM2.5 that occurs due to an additional kg of NOx, by modelling the concentrations with and without an increase in emission in a region (i.e., Europe or USA). For this, a scenario with 20% increase in emissions in a source region was chosen. Concentration changes were determined on a horizontal grid spacing of ca. 2.8° by 2.8°. Moreover, we also derived the value of life lost due to premature deaths associated with the additional NO_x emissions, without future discounting. This was done by multiplying the emission estimates with the mortality incidence per unit of NO_x emission (10.2 deaths/ktonne in Europe and 1.8 deaths/ktonne in the USA), as derived from Tang et al. (2015), and the lower VSL estimate of $7.6 million (2013 US dollars) per life, as reported in a review by Robinson and Hammitt (2015).

3. Results and discussion

Because of the software instalment and subsequent cheating of emission tests by Volkswagen Group, human health damages have been substantially higher than expected from the legal standards of NO_x. In the period from 2009, the start of the fraud, until halfway through 2015 when it was revealed, we estimated that nine million fraudulent Volkswagen cars, sold in the USA and Europe, emitted 526 ktonnes of additional NO_x (Fig. 1A). This is the amount emitted on top of the legal standards, i.e., the amount resulting from the discrepancy between legal standards in the US and Europe and actual emissions in these regions. The subsequent health damages caused by these unforeseen emissions were estimated to be 45

Table 4
Calculation of NO_x emissions above the legal standards.

	Year of sale							Source
	2009	2010	2011	2012	2013	2014	2015	
United States of America								
NO_x emission standard for newly sold cars (mg/km)	43.50	43.50	43.50	43.50	43.50	43.50	43.50	US EPA (2015c)
Average NO_x emission per fraudulent car (mg/km)[a]	904.90	904.90	904.90	904.90	904.90	904.90	904.90	Thompson et al. (2014)
NO_x emission above legal standard per fraudulent car sold (mg/km)	861.40	861.40	861.40	861.40	861.40	861.40	861.40	
2009–2015								
Distance travelled per car (km)	142,968	125,279	106,525	86,789	66,168	44,762	22,673	Lu (2006)
Additional NO_x emission per fraudulent car (kg)	123.15	107.92	91.76	74.76	57.00	38.56	19.53	
Additional NO_x emissions all fraudulent cars (ktonnes)	5.60	5.95	6.27	6.58	5.33	2.99	1.06	
Full service life[b]								
Distance travelled per car (km)	244,850	244,850	244,850	244,850	244,850	244,850	244,850	Lu (2006)
Additional NO_x emission per fraudulent car (kg)	210.91	210.91	210.91	210.91	210.91	210.91	210.91	
Additional NO_x emissions all fraudulent cars (ktonnes)	9.60	11.62	14.41	18.56	19.71	16.33	11.43	
European Union								
NO_x emission standard for newly sold cars (mg/km)	180.00	180.00	180.00	180.00	180.00	80.00	80.00	Delphi (2015)
Average NO_x emission per fraudulent car (mg/km)[a]	904.90	904.90	904.90	904.90	904.90	904.90	904.90	Thompson et al. (2014)
NOx emission above legal standard per fraudulent car sold (mg/km)	724.90	724.90	724.90	724.90	724.90	824.90	824.90	
2009–2015								
Distance travelled per car (km)	121,790	108,808	94,471	78,708	61,450	42,626	22,166	Caserini et al. (2013)
Additional NO_x emission per fraudulent car (kg)	88.29	78.88	68.48	57.06	44.54	35.16	18.28	
Additional NO_x emissions all fraudulent cars (ktonnes)	113.15	100.02	94.36	69.30	54.21	45.89	14.81	
Full service life[b]								
Distance travelled per car (km)	203,683	203,683	203,683	203,683	203,683	203,683	203,683	Caserini et al. (2013)
Additional NO_x emission per fraudulent car (kg)	147.65	147.65	147.65	147.65	147.65	168.02	168.02	
Additional NO_x emissions all fraudulent cars (ktonnes)	189.24	187.22	203.45	179.34	179.71	219.27	135.69	

[a] Average emission from two cars tested, with individual average emissions of 1147 mg/km (n = 8) and 663 mg/km (n = 9).
[b] The maximum full service life was assumed to be 25 years.

Table 5
Calculation of health damages due to NO_x emissions above the legal standards.

	Year of sale							Source
	2009	2010	2011	2012	2013	2014	2015	
United States of America								
DALYs per ktonne NO_x (DALY/ktonne)[b]	20	20	20	20	20	20	20	Tang et al. (2015)
Mortality per ktonne NO_x (incidences/ktonne)	1.75	1.75	1.75	1.75	1.75	1.75	1.75	Tang et al. (2015) [a]
Value of statistical life (million USD/incidence)	7.6	7.6	7.6	7.6	7.6	7.6	7.6	Robinson and Hammitt (2015)
Value of life lost per kg NO_x (USD/kg)	13	13	13	13	13	13	13	
2009–2015								
Additional DALYs (kDALYs)[b]	0.11	0.12	0.13	0.13	0.11	0.06	0.02	
Additional value of life lost (billion USD)	0.01	0.04	0.07	0.09	0.08	0.08	0.07	
Full service life[c]								
Additional DALYs (kDALYs)[b]	0.19	0.23	0.29	0.37	0.29	0.23	0.19	
Additional value of life lost (billion USD)	0.15	0.22	0.26	0.25	0.19	0.15	0.13	
European Union								
DALYs per ktonne NO_x (DALY/ktonne)[b]	90	90	90	90	90	90	90	Tang et al. (2015)
Mortality per ktonne NO_x (incidences/ktonne)	10.23	10.23	10.23	10.23	10.23	10.23	10.23	Tang et al. (2015) [a]
Value of statistical life (million USD/incidence)	7.6	7.6	7.6	7.6	7.6	7.6	7.6	Robinson and Hammitt (2015)
Value of life lost per kg NO_x (USD/kg)	78	78	78	78	78	78	78	
2009–2015								
Additional DALYs (kDALYs)[b]	10.18	9.00	8.49	6.24	4.88	4.13	1.33	
Additional value of life lost (billion USD)	8.8	7.8	7.3	5.4	4.2	3.6	1.2	
Full service life[c]								
Additional DALYs (kDALYs)[b]	17.03	16.85	18.31	16.14	16.17	19.73	12.25	
Additional value of life lost (billion USD)	14.7	14.6	15.8	13.9	14.0	17.0	10.6	

[a] Mortality per ktonne NO_x derived from data reported.
[b] DALY: Disability Adjusted Life Year.
[c] The maximum full service life was assumed to be 25 years.

thousand DALYs (Fig. 1B). Furthermore, the value of life lost due to premature deaths associated with the additional NO_x emissions was estimated to be 39 billion US dollars (Fig. 1C). The vast majority of the health damages occurred in Europe (i.e., 44 thousand DALYs or 38 billion US dollars, compared with 675 DALYs or 450 million US dollars in the USA). This is a direct consequence of two main factors. The first is the much larger amount of fraudulent cars sold in Europe compared with the USA (Table 1). Additional NO_x emissions were therefore also much larger in Europe than in the USA (i.e., 492 ktonnes compared with 34 ktonnes). The second factor relates to the health damage per unit of NO_x emission, as derived by Tang et al. (2015). Mainly because of differences in population density, mortality costs at equal emissions of NO_x are approximately 5.8 times higher in Europe than in the USA (Table 5). When expressed in terms of DALYs, this difference slightly decreases to an approximate factor of 4.5, which can be attributed to the larger amount of years of life lost per incidence of mortality in the USA (Tang et al., 2015).

Health damages could even further increase if the cars are not recalled. Should the fraudulent cars stay on the road over their full statistical life time, additional NO_x emissions due to non-compliance with legal standards are expected to result in 119 thousand DALYs, and a cumulative value of life lost of 102 billion US dollars. Note that if we would have used the upper estimate of VSL reported by Robinson and Hammitt (2015), health costs would have been a factor 1.8 higher. Moreover, US EPA has stated that Volkswagen also equipped an estimated 85,000 3.0-L engine vehicles with emissions-cheating software, in addition to the 482,000 2.0-L engine vehicles (Ewing and Mouawad, 2015; US EPA, 2015a). These additional fraudulent cars were not included in our study. However, Holland et al. (2015) estimated approximately 9 excess expected deaths and 80 million dollars in excess damages from these 3.0-L vehicles.

Both Barrett et al. (2015) and Holland et al. (2015) recently published estimations of additional emissions of NO_x and subsequent health damages due to the fraud committed by Volkswagen Group in the USA. These studies provide a spatially more refined estimation of emissions and subsequent environmental concentrations and health damages, both using an extensive emission-region specific approach. Moreover, contrary to our study, both studies not only consider damages due to PM2.5 formed by NO_x, but also damages due to ozone formation. Furthermore, while Holland et al. (2015) include mortality and morbidity impacts in their health costs estimations, both studies from Barrett et al. (2015) and from us estimate health costs solely from mortality impacts. To derive an estimation of health costs due to mortality, a VSL of 8.1 million (2015 US dollars) is used by Barrett et al. (2015), as recommended by US EPA, while we use the lower VSL estimate of 7.6 million (2013 US dollars), as reported in a recent review by Robinson and Hammitt (2015). Holland et al. (2015) do not specifically report the VSL applied. Despite the differences in methodology, our results for the USA are very similar to those derived by Barrett et al. (2015) and Holland et al. (2015). Table 6 contains a comparison, differentiating between historical emissions and health damages, and future projections thereof.

Our analysis provides an estimate of the public health consequences caused by the exceedance of NO_x emission limits in Europe and the USA, as caused by the fraud committed by Volkswagen Group. We used state-of-the-art information on environmental standards and emission estimates of diesel engines, and the relationship between NO_x concentrations and physical and monetary health consequences. Our results show that health costs in Europe and USA combined are an estimated 5.3 times larger than the 7.3 billion US dollars that Volkswagen Group has set aside to cover worldwide costs related to the diesel emissions scandal (Volkswagen AG, 2015a).

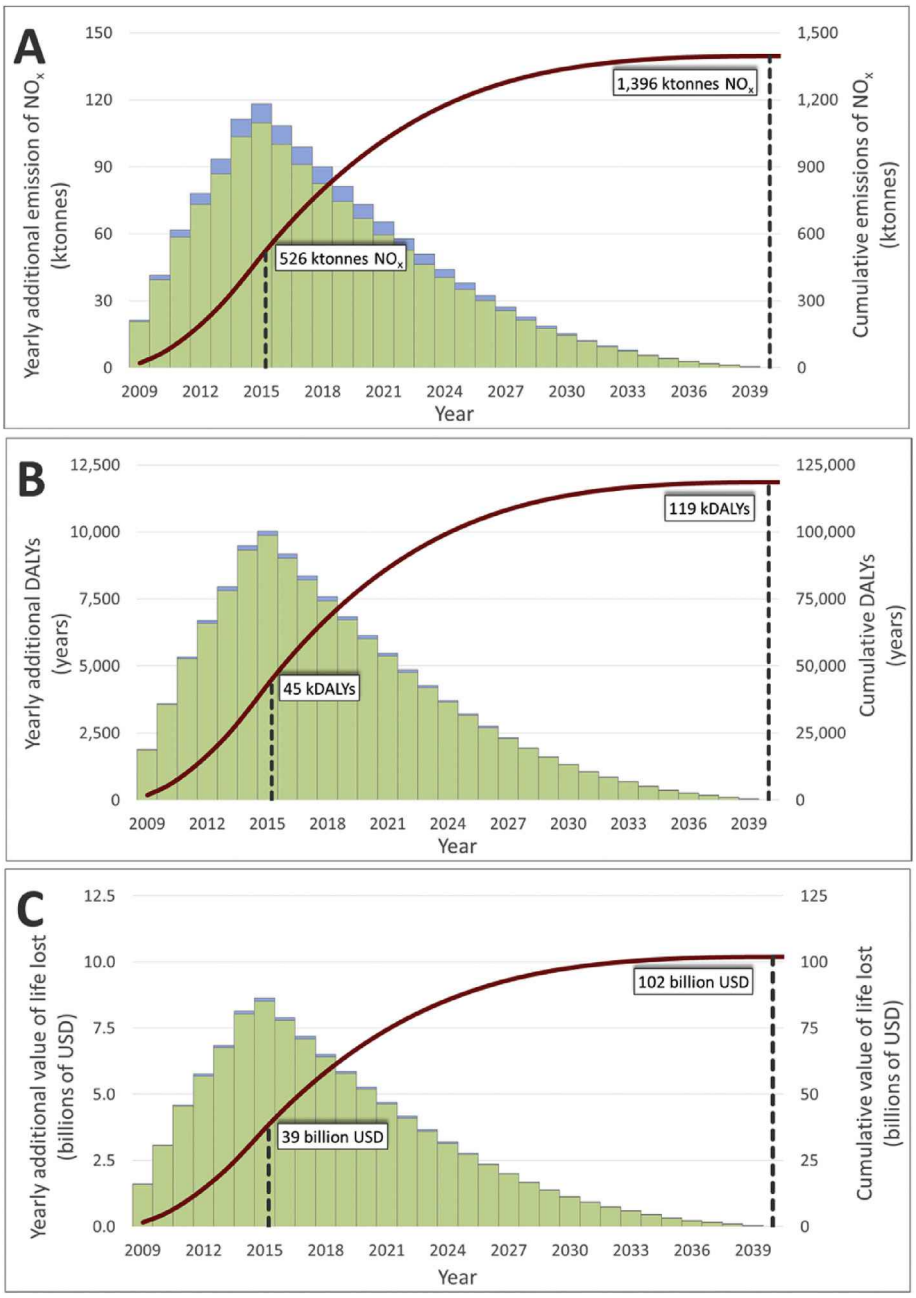

Fig. 1. NO_x emissions above the legal standard in Europe and the USA, resulting from the fraud of Volkswagen (in ktonnes) (A), and subsequent damage to human health, calculated as Disability Adjusted Life Years (in DALYs) (B), and value of life lost (in 2013 US dollars) (C). Green bars represent yearly additional emissions and health damages in Europe; blue bars represent yearly additional emissions and health damages in the USA. Red lines represent cumulative emissions and health damages. Cumulative emissions and health damages until the end of 2015 are reported, as well as after full completion of the service lives of all fraudulent cars. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Comparison of US results with previously published studies.

	Total emissions (ktonnes)		Costs (million US dollars)		Early deaths (incidences)	
	Before 2016	From 2016	Before 2016	From 2016	Before 2016	From 2016
This study	33.8	67.9	450	904.7	59.2	119.1
Barrett et al. (2015) [a]	36.7 (12.3–61.2)	82 (25.8–145.6)	450 (72–1200)	910 (140–2500)	59 (9.7–150)	140 (23–370)
Holland et al. (2015)	45.1	N/A	430	N/A	46.1	N/A

[a] 95% confidence interval between brackets.

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