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Climate effects of non-compliant Volkswagen diesel cars

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Abstract

On-road operations of Volkswagen light-duty diesel vehicles equipped with defeat devices cause emissions of NO_x up to 40 times above emission standards. Higher on-road NO_x emissions are a widespread problem not limited to Volkswagen vehicles, but the Volkswagen violations brought this issue under the spotlight. While several studies investigated the health impacts of high NO_x emissions, the climatic impacts have not been quantified. Here we show that such diesel cars generate a larger warming on the time scale of several years but a smaller warming on the decadal time scale during actual on-road operations than in vehicle certification tests. The difference in longer-term warming levels, however, depends on underlying driving conditions. Furthermore, in the presence of defeat devices, the climatic advantage of ‘clean diesel’ cars over gasoline cars, in terms of global-mean temperature change, is in our view not necessarily the case.

Introduction

While light duty diesel-powered vehicles (diesel vehicles, thereafter) certified to most recent emission standards have been found to effectively reduce emissions of particulate matter (PM), several studies over the past years have pointed to failures to meet the NO_x emission standards under real-world driving conditions [1–13]. A particularly serious case is the recent revelation of defeat devices installed in diesel vehicles of companies including Volkswagen (VW), Audi, and Porsche (collectively VW thereafter), so-called Dieselgate [14]. They deliberately tuned vehicle emissions to pass the certification tests while violating the respective emission standards during actual road operations to improve driving performances and fuel consumptions [15–17]. There were several precedents for defeat devices in the diesel industry [18], but the scale of VW violations was unprecedented. As many as 11 million VW vehicles worldwide have been approved in laboratory tests by relying on such cheating software [19]. Such fraudulent vehicles amount to 40% of the total number of VW passenger cars sold in the European Union during the period 2009–2015 [20]. In the US, diesel NO_x emissions measured

on the road are up to 40 times higher than the corresponding standards [21] (T2014, thereafter). The apparent inconsistency between the vehicle emissions during the laboratory tests and those in the actual driving, let alone the scale of systematic violations, eroded the public trust in the car industry and led to a range of concerns in environmental, health, regulatory, legal, financial, and ethical dimensions. This is a first study that attempts to clarify what the non-compliant diesel vehicles mean for climate change.

Currently, CO₂ emissions from road transport take up approximately 17% of the global fossil fuel CO₂ emissions [22], which primarily cause man-made climate change [23]. NO_x emissions from diesel vehicles pose a threat to urban air quality [24–28]. For the particular VW case, human health studies estimated that the diesel vehicles with sophisticated software deployed have caused or will have caused a small, but positive number of deaths in the US: early deaths of approximately 59 persons with a 95% range of 4.6 to 130 during the violation period of 2008–2015 [29], 46 persons with a one sigma range of 40 to 52 for the same period [30], 5 to 50 persons per year [31], 59.2 persons during the violation period [20], and 12 persons for the same period (only in California) [32]

(note that the limited treatments of uncertainties have been in dispute [33, 34]). There are also a few studies investigating the health impacts in Europe [20, 35, 36]. From the climate perspective, this issue has been raised prior to the Paris Agreement [37] without however being substantiated by any quantitative analysis. Diesel vehicle exhaust affects the climate in a complex manner involving competing effects over different time scales [38]: NO_x emissions lead to an increase in the tropospheric ozone (O₃) concentration for a short period of time (i.e. a warming effect) but reduce the methane (CH₄) concentration (i.e. a cooling effect) which operates on a decadal timescale [39], which is further superimposed by a more persisting and in part even century-scale warming caused by CO₂ [40, 41]. Furthermore, there are aerosols such as black carbon (BC) and organic carbon (OC) that influence the short-term climate response but in opposite directions [42]. This raises the question as to what the net climate effect of non-compliant diesel engine exhaust over different time horizons is.

It is a widespread belief that vehicles equipped with improved diesel engine technologies, or so called 'clean diesel' [43], are more climate friendly than conventional gasoline vehicles because of the generally better fuel economy of diesel vehicles due to a higher volumetric energy content in diesel fuels. This argument encouraged a shift from gasoline to diesel vehicles and contributed to the much increased share of diesel cars in Europe for the past two decades [28, 44, 45]. Such an argument was also used by VW, which claimed that diesel cars are needed in order to reduce CO₂ emissions [46]. The diesel concept is further supported by the fuel economy agreement established between the European automobile manufacturers and the European Commission to address the Kyoto Protocol in 1997 [47].

However, actual climate benefits of switching from gasoline to diesel vehicles have been deeply questioned due to a number of confounding factors [47–51]. Our previous study [52] (T2012, thereafter) showed that, under idealized settings, switching from gasoline to diesel vehicles with comparable engine performances contributes to a lower warming in the long run. This is because diesel vehicles generally emit less CO₂ than gasoline vehicles per unit driving distance under equal driving conditions [50], assuming that the emissions of other pollutants are held at the Euro standard levels. From a short-term perspective, on the other hand, diesel vehicles contribute more to the global warming because of the net warming effects caused by the emissions of NO_x and PM (note that the PM effect is small for diesel vehicles in accordance to latest emission standards). The recent revelation that defeat device-equipped diesel vehicles emit far larger amounts of NO_x than permitted made us revisit this issue.

In light of the background above, our study addresses the following two questions:

1. What are the climate impacts caused by a VW diesel vehicle in the *non-compliance* mode (as revealed on the road) compared to those in the *compliance* mode (as measured in the laboratory)?
2. Does the climatic advantage of clean 'diesel' hold for a non-compliant diesel vehicle? In other words, does a *diesel* vehicle in the non-compliance mode impact the climate less in magnitude relative to a *gasoline* vehicle of comparable characteristics?

Our study aims to clarify in what way much higher on-road NO_x emissions from diesel vehicles might influence the climate. More specifically, a few studies [30, 53] characterize the present human health impacts due to the additional NO_x emissions from diesel cars as a tradeoff with the avoided future climate impacts as a result of saved CO₂ emissions through better mileage, without addressing climate effects associated with non-CO₂ components. This study intends to inform such debate of a more comprehensive climatic view.

Methods

Model

We follow the approach used in T2012. Changes in the global-mean temperature over time to the emissions of CO₂, CH₄, NO_x, CO, non-methane volatile organic compounds (NMVOCs), BC, and OC (fractions of PM) from diesel and gasoline vehicles are quantified using an analytical climate model [38]. The model sufficiently represents relevant atmospheric chemistry processes operating on different time scales and their interplays. This feature is important because the outcome depends critically on how the short-term O₃, medium-term CH₄, and long-term CO₂ play out over time.

The model is based on a simple upwelling-diffusion scheme that consists of two boxes: the upper box representing the atmosphere and the mixed layer of the ocean and the lower box for the deep ocean. Hence, the model accounts for the thermal inertia of the climate system through heat exchange with the deep ocean. The equilibrium climate sensitivity for doubling CO₂ is assumed to be 3.37 °C, which is the average of CMIP5 models [54] and falls within the likely range of 1.5 °C–4.5 °C [23]. We consider the impacts of CO₂, BC (including the effect of BC deposition on snow), OC, nitrate aerosols, O₃ and CH₄ perturbations induced by emissions of NO_x, CO and NMVOCs, and the effect of direct CH₄ emissions. The temporal evolution of the atmospheric CO₂ concentration in response to its release is computed using the impulse response function [41]. The radiative efficiency of CO₂ is based on [23]. The perturbation caused by a pulse emission of CH₄ as well as aerosols is assumed to follow a simple exponential decay with one time scale determined by the atmospheric residence time of the respective

Table 1. Emission factors for CO₂, CH₄, NO_x, CO, NMVOCs, and PM from the operation of diesel vehicle *DA* (VW Jetta 2012 Diesel), diesel vehicle *DB* (VW Passat 2013 Diesel), and gasoline vehicle *GA* (VW Jetta 2012 Gasoline) used in this study. For details in driving conditions *SG* and *HI*, see Methods. ‘Compliance’ and ‘non-compliance’ driving mode indicate that emissions are measured in the laboratory and on the road, respectively. Emission factors for gasoline vehicle *GA* were measured in the laboratory. Uncertainties in emission factors are shown in table S1 of supplementary information available at stacks.iop.org/ERL/13/044020/mmedia.

Vehicle type	Driving condition	Driving mode	CO ₂ g/km	CH ₄ mg/km	NO _x mg/km	CO mg/km	NMVOCs mg/km	PM mg/km
Diesel vehicle <i>DA</i> (<i>Jetta 2012 D</i>)	<i>SG</i>	<i>Compliance</i>	168	18.5	4.93	74.8	3.28	0.709
	<i>HI</i>	<i>Compliance</i>	174	0.12	48.5	6.2	0.62	0.621
	<i>SG</i>	<i>Non-compliance</i>	212	36.6	1235	89	1.9	0.076
	<i>HI</i>	<i>Non-compliance</i>	156	29.0	1060	59	1.5	1.45
Diesel vehicle <i>DB</i> (<i>Passat 2013 D</i>)	<i>SG</i>	<i>Compliance</i>	166	10.4	13.8	110	18.8	0.304
	<i>HI</i>	<i>Compliance</i>	171	0.52	2.38	6.0	1.99	0.226
	<i>SG</i>	<i>Non-compliance</i>	238	5.7	742	107	0.3	0.309
	<i>HI</i>	<i>Non-compliance</i>	152	4.3	508	44	0.2	0.129
Gasoline vehicle <i>GA</i> (<i>Jetta 2012 G</i>)	<i>SG</i>	—	201	2.1	8.20	280	19.5	1.24
	<i>HI</i>	—	184	5.03	4.16	1392	13.4	0

component. The CH₄ perturbation lifetime is 12 years and the radiative efficiency of directly emitted CH₄ also follows [23]. The effect of changes in O₃, CH₄ and long-term CH₄-induced O₃ caused by emissions of NO_x, CO and NMVOCs are estimated using the parameterizations shown in table 4.11 [55] (see also [56]). This parameterization is used in simple climate models applied to transport studies [38, 52]. For input to the simple climate model, PM emissions in the emission factors are split into BC and OC emissions using fractions reported by [57]. Radiative efficiencies of BC and OC are taken from the results of the AeroCom project [58] and we assume lifetimes of 7.1 and 7.6 days, respectively. The effect of BC deposition on snow is taken into account (see T2012). The radiative efficiency of nitrate aerosols is derived from a global perturbation in present-day NO_x emissions simulated by the global chemistry-transport model OsloCTM3 [59] and we adopt a lifetime of 5 days. Emissions of NO_x are assumed to be NO₂ for the sake of simplicity [2]. Our analysis does not address the climate effects of secondary aerosols from vehicle emissions in spite of their potential importance [60]. Quantification of associated climate forcing still requires related processes to be fully included in state-of-the-art climate models [61].

Emission data

To the simple climate model we prescribe emissions of various components contained in vehicular exhausts. As in T2012, the current analysis considers the operation of single vehicles, not the fleet. We compile a set of emission data for two types of diesel vehicles (*DA* and *DB*) under two different driving conditions (*stop-and-go* (*SG*) and *highways and hills* (*HI*)) in the compliance or non-compliance mode (table 1). For the non-compliance mode, we directly apply the on-road emission factors (g km⁻¹) reported in T2014, which were measured under diverse driving conditions (i.e. without limiting NO_x emissions presumably to enhance driving performance and fuel economy). For the compliance mode, we use emission factors obtained from test cycles (i.e. laboratory measurements performed by US Environmental Protection Agency

(EPA) to certify vehicles prior to market release [8]). To single out the effect of defeat devices as cleanly as possible, we looked to test cycle data for vehicles of equal characteristics (e.g. engine sizes and vehicle weights) under comparable driving conditions (e.g. vehicle speed, acceleration, and engine temperature) [62]. While most previous analyses make assumptions for NO_x emissions to discern the impacts on air quality from defeat devices [29–31, 35], we use directly measured emission data to study climate impacts, which are influenced by many relevant gases and aerosols. There are other emission data for diesel vehicles obtained from on-road measurements [8]. However, we use only the specific sets of emission data without mixing them altogether to keep the underlying driving conditions comparable. Furthermore, we obtained a set of corresponding emission data for gasoline vehicle *GA*, a counterpart of diesel vehicle *DA*. Emission data from the gasoline counterpart for vehicle *DB* were not found. Further issues associated with the comparability between the on-road and laboratory emission data are discussed below.

The *non-compliant diesel* emission factors used in our study are based on emission measurements on the road, under which defeat devices are presumably used with an apparent intention to enhance the fuel economy (i.e. less CO₂ emissions per unit distance) in exchange for larger NO_x emissions [17]. Such emission factors are obtained from two types of vehicles *DA* and *DB* studied in T2014, whose makes and names are anonymized in the original study but now widely known as a VW Jetta 2012 and a VW Passat 2013 [29]. They serve as contrasting examples. While these vehicles have an equal engine displacement of about 2 L and equivalent maximum engine power and torque, they are equipped with different NO_x after-treatment technologies [7, 9, 11]: a lean-NO_x trap (LNT) system for Jetta and a urea-based selective catalytic reduction (SCR) for Passat. LNT is typically installed to small low-cost vehicles in Europe and known to fail to capture NO_x in uphill and highway driving conditions. SCR is used more often in larger vehicles and dominant in the US market, where the regulations for NO_x are more stringent than in Europe.

On the contrary, the *compliant diesel* emission factors are taken from test cycles in the laboratory, during which the vehicles appear to comply with respective emission standards by suppressing NO_x emissions while accepting poorer fuel economy (i.e. more CO_2 emissions). Such emission factors come from particular test groups of vehicles (i.e. CVWXV02.0U5N and DVWXV02.0U4S) [63], which contain the above-mentioned two types of vehicles. Furthermore, the *gasoline* emission factors are obtained from the test group designated as CVWXV02.0U36, which includes a gasoline counterpart of vehicle *DA* with a comparable engine displacement to come up with a so-called ‘matched pair’ [50]. Emission factors of the above-mentioned three test groups were taken from the associated Applications for Emissions Certification submitted by VW to EPA (<https://iaspub.epa.gov/otaqpub/>). No uncertainty ranges are reported for these emission factors.

To extract the effects of defeat devices by differentiating the results from on-road (i.e. non-compliant) and laboratory (i.e. compliant) emissions, we keep the underlying driving conditions for the emission datasets closely comparable. As for the laboratory emission factors, there are currently five types of test cycles that are mandated in the US. Closely relevant to our analysis are the following two test cycles: (i) EPA Federal Test Procedure (FTP) (commonly known as FTP-75) and (ii) US06, a Supplemental FTP [64]. On the other hand, the on-road emission factors were obtained from the following five different routes: (i) highway, (ii) urban (Los Angeles), (iii) rural-up/downhill, (iv) urban (San Diego), and (v) urban (San Francisco). As T2014 argues, the driving condition for FTP-75 is similar to those in the second and fourth routes with respect to the average and maximum vehicle speeds (tables 3.3 and 3.4 of T2014), representing urban driving characterized as low speeds and frequent stop-and-goes (i.e. driving condition *SG*). Likewise, that for US06 is in an equivalent category with those in the first and third driving routes, which is characterized as high speeds including uphill and downhill driving (i.e. driving condition *HI*). Thus, such grouped emission data serve as a basis for comparison to distil the climate effects of defeat devices.

While the test-cycle emission factors discussed above are, to our knowledge, the closest to what would be expected from the originally tested vehicles with defeat devices activated, there are irreconcilable gaps. FTP-75 consists of three phases—it starts with a cold start phase (generally called Bag 1), which is followed by a cold stabilization phase (Bag 2) and a hot start phase (Bag 3). It is known that a cold engine generates larger NO_x emissions than a warm engine (e.g. figure 3.32 of T2014) [65] and that the thermal efficiency is generally lower at a cold start [66]. In the on-road experiments of T2014 the engines were, on the contrary, prepared warm prior to the emission measurement. This indicates that our emission data based

on FTP-75 (especially that for NO_x) can be overestimated because of the cold start phase included. This issue needs to be kept in mind when one interprets our results. This bias cannot be corrected because emission factors from each bag are not available in the EPA database (US EPA, 12 May 2016, *personal communication*; Freedom of Information Act (FOIA) online, 13 June 2016, EPA-HQ-2016–007076).

Experimental design

With these emission data, we simulate the temperature responses in two idealized cases: (i) one year of vehicle emissions and (ii) sustained emissions over the vehicle lifetime (i.e. 15 years assumed). The first experiment provides insight to the fundamental structure of the problem by comparing the various climate impact mechanisms acting on different time scales. The second experiment offers an outcome that are arguably designed for more realistic interpretations. The period of 15 years is also used by T2012 and consistent with estimates of the average vehicle lifetime in the US [67]. Although emissions are known to deteriorate over the useable life of cars [68, 69], we assume constant emission levels over the 15 year period in the analysis.

All the reference simulations are based on the best estimates of input data and parameters. These input data and parameters, however, have associated uncertainties. As we focus on the interplay among different climate forcings, we probe the uncertainties in emission factors and radiative forcing (tables S1 and S2). For the emission factors of non-compliant diesel vehicles, we use the standard deviations based on T2014. Due to lack of data, we apply the same standard deviations to the compliant diesel vehicles and the gasoline vehicle. Uncertainties in the radiative forcing of BC and OC are derived from the multi-model results in the AeroCom Phase II experiment [58], while those of CO_2 , CH_4 , O_3 precursors (NO_x , CO, and NMVOC), and nitrate are based on [70]. To establish ranges in the global-mean temperature response, we perform Monte Carlo runs. The uncertainty analyses were conducted separately for emission factors and radiative forcing. In each of the two sets of runs, individual sources of uncertainties are treated as being independent and are assumed to follow normal distributions. Although there are sources of uncertainties that are theoretically correlated (e.g. emission factors of BC and OC; see a related discussion in [71]), we do not account for correlations for the sake of transparency.

Results

Global-mean warmings caused by one-year on-road operations of diesel vehicles *DA* and *DB* (i.e. in the non-compliant mode) exhibit more complex changes than those implied from laboratory emissions (figures 1 (a) and (b)). This is due to the excess NO_x emissions during on-road operations, which manifest

themselves as competing climate effects over a range of time scales. The common features in the warming from on-road emissions of vehicles *DA* and *DB* are characterized first by strong short-term warming. This is mostly caused by the tropospheric O_3 response to the excess NO_x emissions (figure S1)—contributions from BC are rather small. In the mid-term, the warming drops drastically as a result of the reduction in the CH_4 concentration [39] and along with the rapid decay in the short-term O_3 response. This is, however, followed by long-term warming due to the CO_2 emissions, as the CH_4 cooling disappears. Note that the short-term warming and the mid-term cooling are more enhanced in the results for vehicle *DA* than those for vehicle *DB*. This is owing to the NO_x after-treatment technology typically used in small cars like vehicle *DA*, which is known to release a substantial amount of NO_x under certain conditions.

Temperature uncertainties from the on-road emission factors of diesel vehicles *DA* and *DB* are relatively small at 5 years after emissions and become larger at 20 years and smaller at 50 and 100 years (figure 1). More distinct characteristics can be seen in temperature uncertainties from radiative forcing, which are remarkably large at 20 years (figure S2) among other points in time, reflecting the large uncertainty from the NO_x radiative forcing (table S2). The uncertainties are substantially reduced at 50 years as associated forcing terms disappear over time. The remaining long-term uncertainties stem from CO_2 forcing.

On the contrary, warmings caused by laboratory emissions from diesel vehicles *DA* and *DB* (i.e. in the compliance mode) and gasoline vehicle *GA* show a very different temporal pattern, peaking around a decade after the emissions and persisting for a long term (figure 1), which is mostly driven by CO_2 emissions (Figure S1). Temperature uncertainties from radiative forcing are mainly determined by the uncertainty in CO_2 forcing and are thus small in the short- and mid-terms because of generally small amounts of pollutant emissions (figure S2).

The abovementioned fundamental features of the results based on one-year emissions are kept in the results from the analysis using 15 year sustained emissions (figure 2). Although the absolute magnitudes of long-term temperature changes are obviously different, the relative levels (e.g. the difference between on-road and laboratory results) are not qualitatively different in the mid- to long terms. The warming behaviors during the first 15 years are worth noting. The temperature rises rapidly in all cases of sustained emissions, but in the on-road cases of vehicle *DA*, the rate of temperature increase starts to decline several years after the emissions start. This is caused by the cooling effect induced by decreasing CH_4 concentrations, which partially offsets the warming built up from the sustained emissions. When the sustained emissions stop, the warming in all the diesel cases shows a sharp decline, reflecting the cessation of short-term O_3 response.

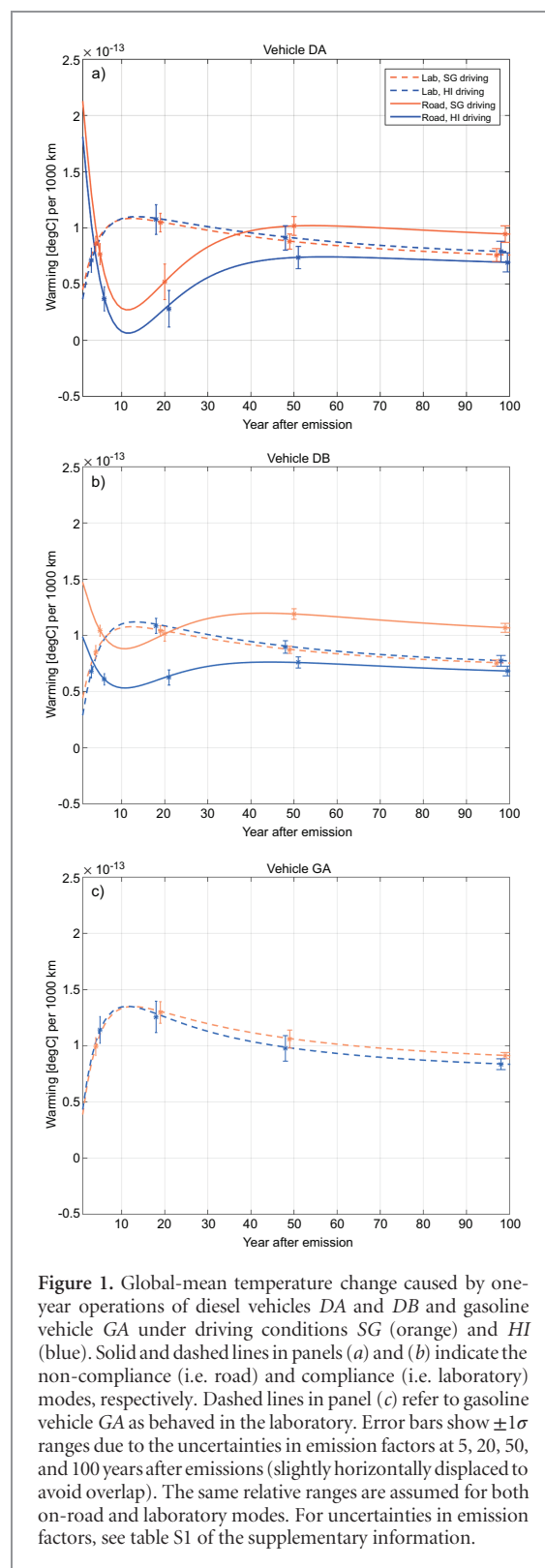


Figure 1. Global-mean temperature change caused by one-year operations of diesel vehicles *DA* and *DB* and gasoline vehicle *GA* under driving conditions *SG* (orange) and *HI* (blue). Solid and dashed lines in panels (a) and (b) indicate the non-compliance (i.e. road) and compliance (i.e. laboratory) modes, respectively. Dashed lines in panel (c) refer to gasoline vehicle *GA* as behaved in the laboratory. Error bars show $\pm 1\sigma$ ranges due to the uncertainties in emission factors at 5, 20, 50, and 100 years after emissions (slightly horizontally displaced to avoid overlap). The same relative ranges are assumed for both on-road and laboratory modes. For uncertainties in emission factors, see table S1 of the supplementary information.

Now, to answer the first research question, we found that the additional climate impacts of the non-compliant vehicles, taken as the difference in the impacts between the on-road and laboratory cases using the 15 year sustained emissions, are highly contingent on the time scale of concern as well as the underlying driving patterns (figure 3). The non-compliant diesel vehicles clearly produce larger climate impacts in the short term than the compliant diesel vehicles of equal

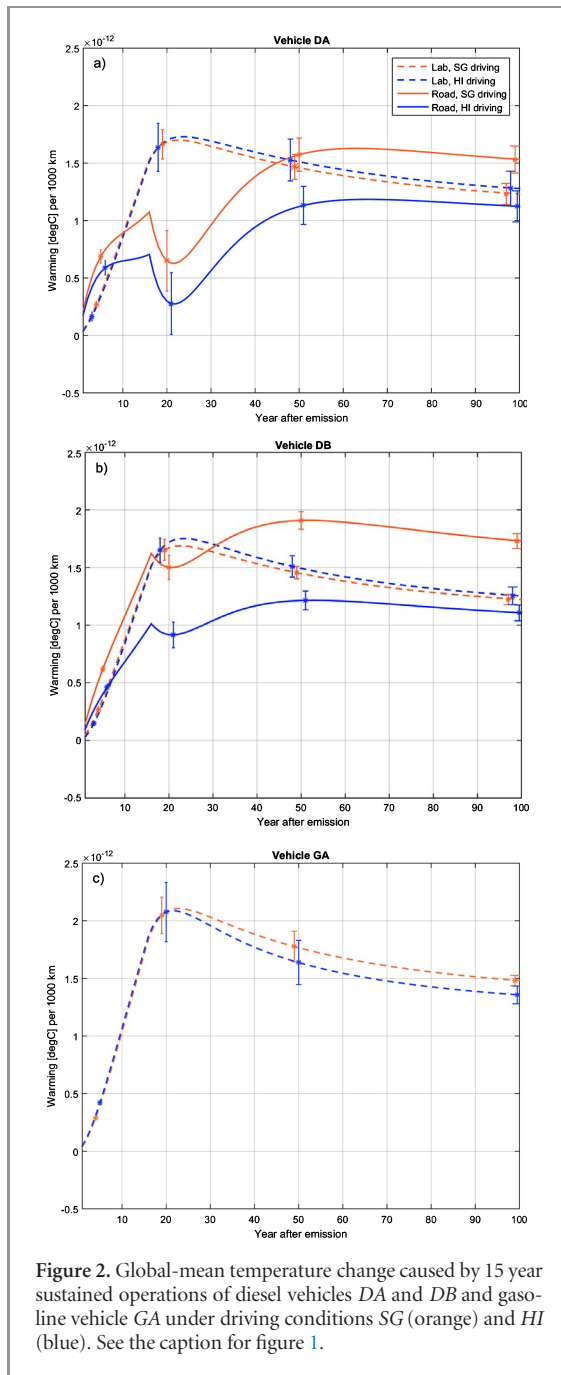


Figure 2. Global-mean temperature change caused by 15 year sustained operations of diesel vehicles *DA* and *DB* and gasoline vehicle *GA* under driving conditions *SG* (orange) and *HI* (blue). See the caption for figure 1.

characteristics do, but they create smaller impacts in the mid-term. On the other hand, differences in the long-term temperature changes, which are solely determined by the differences in CO_2 and unaffected by NO_x (figure S1), are inconclusive in terms of the direction of change. For both vehicles *DA* and *DB*, the on-road emissions lead to a larger long-term warming under driving condition *SG* (24% and 42% more enhanced warmings after 100 years, respectively) but a smaller long-term warming under driving condition *HI* (12% less enhanced warmings after 100 years for both vehicles), as far as the best estimates for emission factors and radiative forcing are concerned.

It is noteworthy that the finding under driving condition *SG* above is not compatible with the trade-off

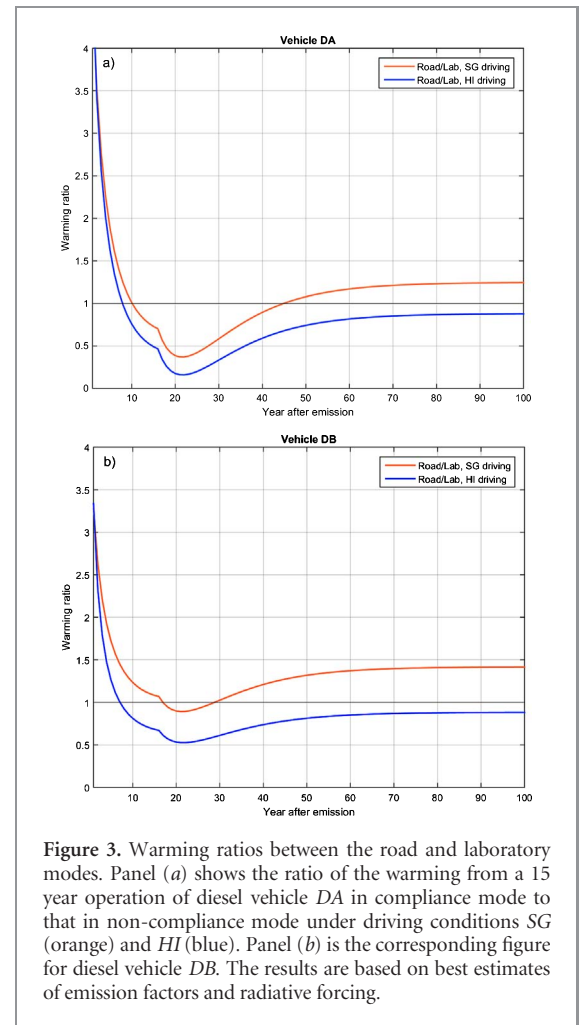


Figure 3. Warming ratios between the road and laboratory modes. Panel (a) shows the ratio of the warming from a 15 year operation of diesel vehicle *DA* in compliance mode to that in non-compliance mode under driving conditions *SG* (orange) and *HI* (blue). Panel (b) is the corresponding figure for diesel vehicle *DB*. The results are based on best estimates of emission factors and radiative forcing.

that defeat devices intend to manipulate: (i) improve the fuel economy (i.e. decrease CO_2 emissions) during on-road operations by allowing excessive NO_x emissions and (ii) compromise the fuel economy (i.e. increase CO_2 emissions) during laboratory operations by suppressing NO_x emissions to pass the certification test [17]. The exact reasons for the larger CO_2 emissions on the road under driving condition *SG* are unclear, but it could be an indication that differences in the underlying driving conditions between the laboratory and on-road cases (see Methods) might have affected the results. Furthermore, one may speculate the influence from additional fuel usage accompanied by diesel particulate filter (DPF) regeneration events [72], which results in additional CO_2 emissions—however, they do not clearly explain the discrepancy because there is no difference in the number of DPF regeneration events between driving conditions *SG* and *HI* (table 4.2 of T2014).

Regarding the second question, the case for the climatic advantage of ‘clean diesel’ vehicles in the presence of defeat devices, likewise, depends on the time scale and the driving condition (figure 4). The theoretical emissions in the compliance mode indeed indicate slightly smaller climate impacts by 6%–20% than those

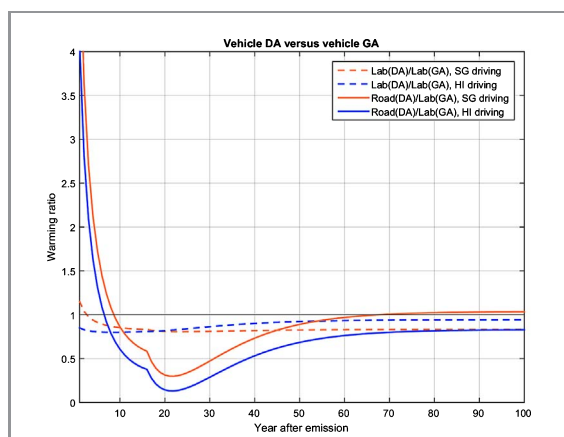


Figure 4. Warming ratios between the diesel and gasoline vehicles. The figure shows the ratio of the warming from a 15 year operation of diesel vehicle *DA* to that of gasoline vehicle *GA* when diesel vehicle *DA* is in compliance mode (dashed lines) and non-compliance mode (solid lines). Orange and blue lines indicate driving conditions *SG* and *HI*, respectively. The results are based on best estimates of emission factors and radiative forcing.

from the gasoline vehicle of comparable characteristics over a wide range of time scale, assuming the best estimates of emission factors and radiative forcing. However, in the non-compliance mode, differences in the temperature changes are either positive or negative: a slightly larger long-term warming under driving condition *SG* (3% more enhanced warming after 100 years) as opposed to a smaller long-term warming under driving condition *HI* (17% less enhanced warming after 100 years). It should however be noted that the fuel advantage of diesel vehicles becomes marginal recently due to the continuing improvement of gasoline engine technology, diminishing the long-term climate benefits of diesel vehicles.

We have thus far looked into temperature changes at end-points in time. There are types of impact that, however, concern more the cumulative warming over time. To emphasize the plurality of ways in which results are evaluated or impacts are perceived, we put together the results in figures 5 and 6 from two different temporal perspectives: (i) *end-point* perspective, in which the impacts are evaluated at the end-point of the specified time horizon as discussed previously, and (ii) *integrated* perspective, in which the impacts are quantified by integration over the course of the time horizon. Note that the integrated perspective can also be framed as *averaged* perspective when impacts are normalized with respect to time. Instrumental to this temporal perspective issue are debates surrounding emission metrics that are used to define the relative impacts of non- CO_2 emissions on the basis of CO_2 emissions [23, 73–82]. Emission metrics depend likewise on the temporal perspective as well as the time horizon. A relevant outcome of the metric debates is that the end-point perspective is aligned more with the cost-effectiveness framework such as the temperature stabilization in the Paris Agreement, while the

integrated perspective fits better with the cost-benefit framework addressing climate impacts more explicitly [83].

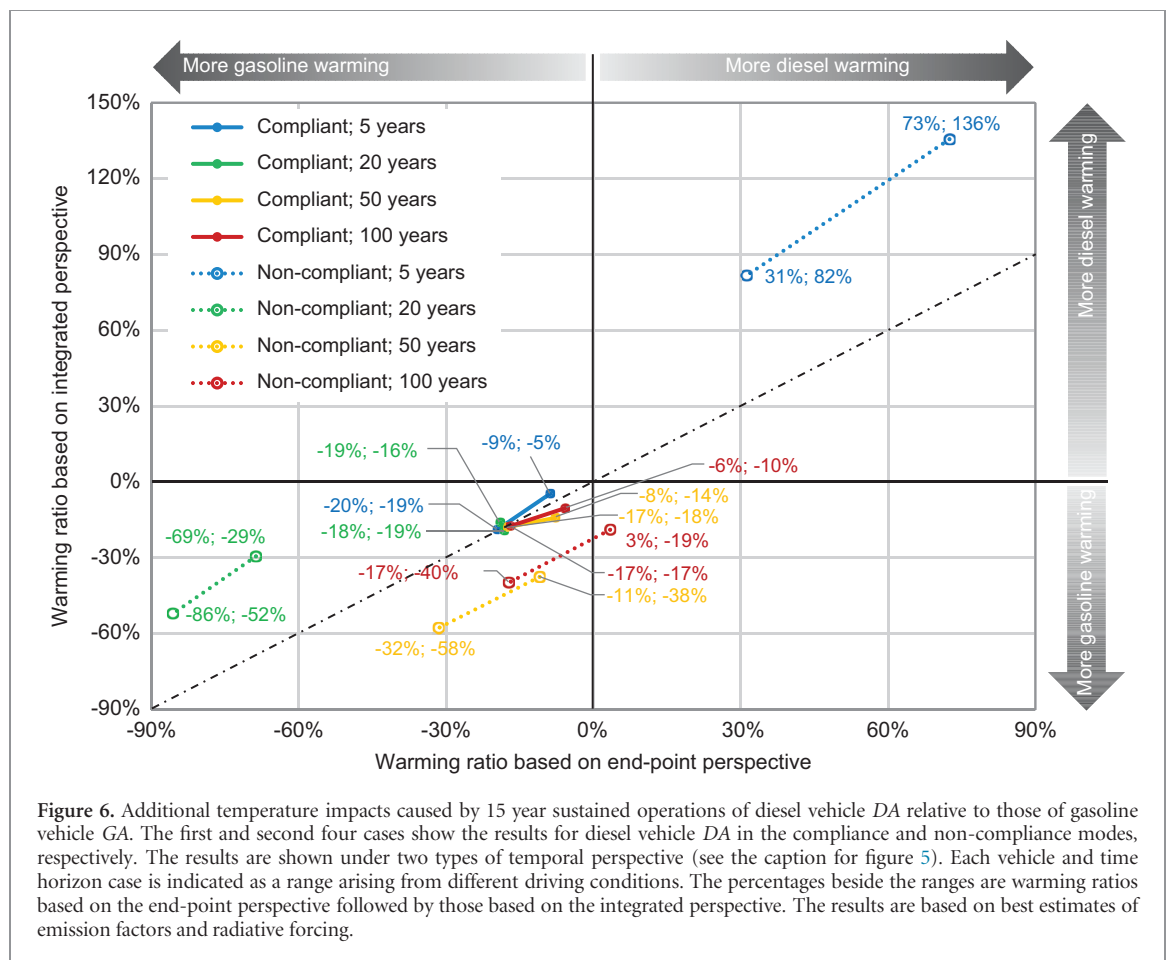
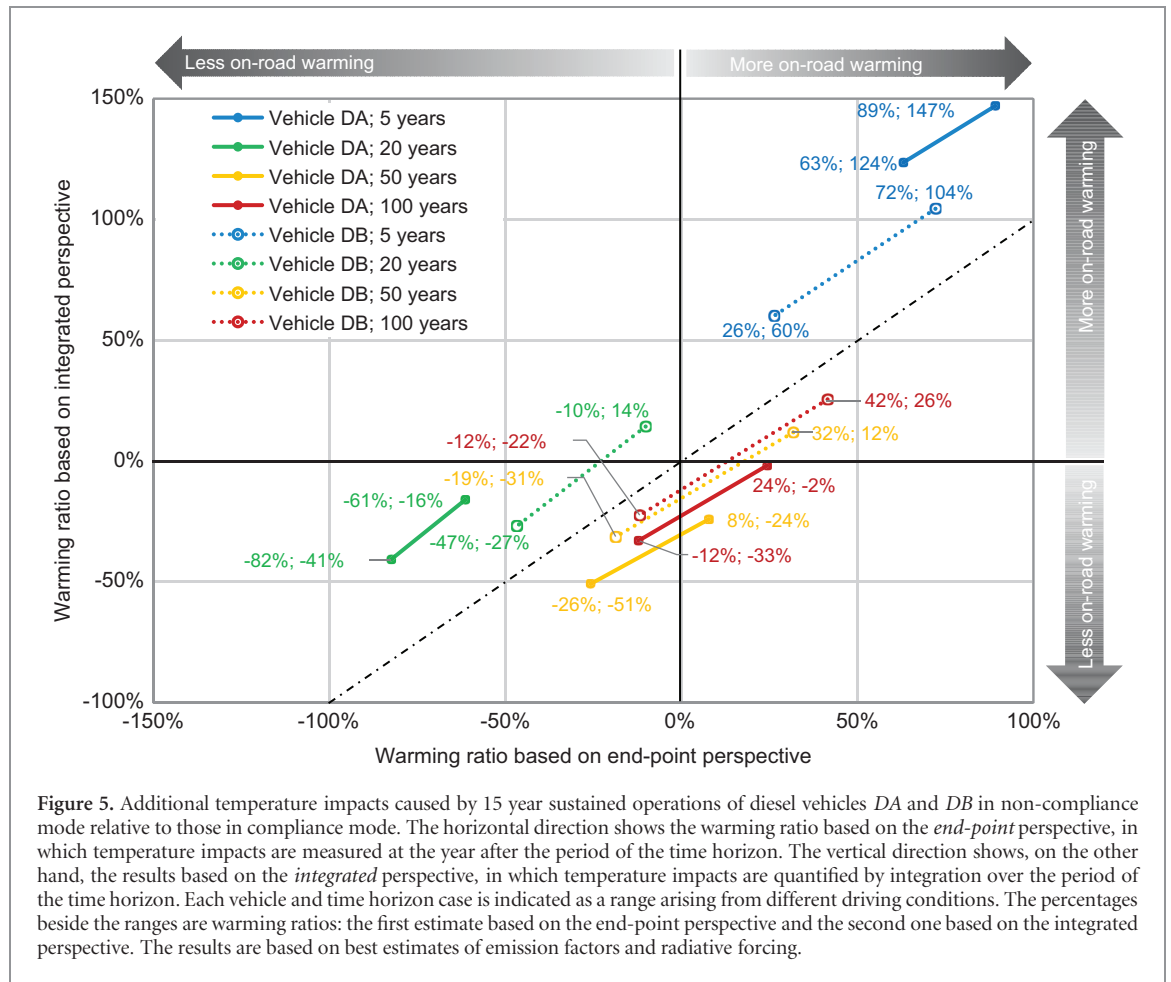
Figures 5 and 6 show that temperature impacts seen from the integrated perspective put more emphasis on impacts carried from previous periods than those from the end-point perspective. For instance, the warming ratio between the road and laboratory modes for vehicle *DA* range from -12% to 24% and from -33% to 1.8% under the end-point and integrated 100 year time horizons, respectively. The ranges stem from different driving conditions, with the best estimates of emission factors and radiative forcing assumed. The corresponding quantity for vehicle *DB* is from -12% to 42% and from -22% to 26% , respectively.

The choice of the temporal perspective (i.e. end-point vs. integrated) however does not influence our broad conclusions. Regardless of the choice of temporal perspective, the answer to the first question depends on the time scale and the underlying driving conditions. The additional long-term temperature change from the non-compliance mode is still either positive or negative, although the long-term warming level looks lower with the integrated perspective because of the offsetting effects discussed above. Regarding the answer to the second question, the warming differences in question depend again on the time scale and the driving conditions. Nevertheless, our results suggest that the legitimacy of climate friendly ‘clean diesel’ indeed appears to be the case if the vehicles are truly in compliance; however, this is not necessarily the case in the presence of defeat devices.

Discussion

We have taken a first step toward quantifying the climate impacts caused by the emissions from non-compliant diesel vehicles during on-road operations by taking the VW emission cheating as an illustrative example. Our study employs a transparent approach, dealing with single specific vehicles, not the fleet, under well-documented driving conditions to understand the fundamental structures of the problems at hand. In doing so, we emphasize the need to include the effects from non- CO_2 components (not just CO_2) in the analysis, which are often ignored in the previous debates on the climate benefit of diesel vehicles. We are explicit about the plurality of ways to evaluate climate impacts with respect to the time horizon (e.g. 20 years vs 100 years) and the temporal perspective (e.g. end-point or integrated), the awareness of which is important in dealing with multiple components with different atmospheric characteristics.

We conclude the following two points: (1) the use of defeat device-installed diesel vehicles can create additional temperature impacts in a complex manner over time, depending on the driving conditions, and (2) the climatic advantage of ‘clean diesel’ does not



necessarily hold in the presence of defeat devices. To scale up our results to elucidate the climate impacts from the whole affected fleet (i.e. the entire Diesel-gate), our analysis suggests that it would be crucial to consider the underlying driving conditions realistically. Quantifying actual climate impacts can also be challenged by a number of confounding factors including the so-called rebound effect [47–51]. Furthermore, even in our idealized and well-controlled setting, the climate impacts from diesel vehicles are complex, whose interpretation requires various perspectives.

As a final remark, we generally support the direction of new emission regulations requiring more data from on-road operations, beyond laboratories that have so far been considered. On the other hand, enforcing stricter and more comprehensive emission standards do not necessarily lead to an improvement and may possibly create another loophole [84]. Designing next-generation policies tackling diesel vehicle exhaust requires input from multiple perspectives as well as interdisciplinary discourse. Climate impacts should therefore be addressed as one of the central issues together with human health [13, 20, 29–32, 35, 36], climate policies [44, 45, 47], engine technologies [85], economics [84], legitimacy [86], and ethics [14, 53] to better inform policymaking associated with diesel vehicle exhaust.

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