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A negative emission internal combustion engine vehicle?

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HIGHLIGHTS

- Modern internal combustion engines can have very low pollutant emissions.
- Some places in the world can have very high levels of atmospheric pollutants.
- It is possible that modern vehicles can be negative emission.
- However, the circumstances under which this can happen on average are limited.
- A spreadsheet tool is available for readers to use their own values.

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ABSTRACT

Modern internal combustion engine vehicles carry extensive exhaust aftertreatment systems that have the potential to reduce their tailpipe pollutant emissions to near-zero, or even within the zero levels of measurement equipment in real-world conditions. It has been reported, therefore, that such vehicles have the potential to have tailpipe pollutant levels lower than the air intake of the vehicle – that they are cleaning the ambient air. This study investigates this hypothesis using a range of internal combustion engines and real-world emissions data alongside pollutant (in this case nitrogen dioxide and particulate matter) data from around the world and the accuracy of the instrumentation typically used to measure tailpipe emissions. The results show that it is unlikely that a modern internal combustion engine vehicle will clean ambient air, even at extreme pollution levels, although it is possible. However, where a vehicle inlet is in the plume of a dirtier vehicle or the pollution measured is among the highest values recorded globally, the pollution reduction can be substantial.

1. Introduction

Around the world, poor air quality is a substantial risk to human health, with the World Health Organisation (WHO) estimating that 4.2 million early deaths occur worldwide as a consequence (Ostro et al., 2018). Particular pollutants of concern include oxides of nitrogen (NO_x), fine particulate matter (PM), ozone, sulphur dioxide, carbon monoxide (CO), ammonia, and volatile organic compounds (VOC); amongst others (Harrison, 2001).

The WHO defines guideline values for pollutants, including NO_2 (10 $\mu g/m^3$), PM_{10} (15 $\mu g/m^3$), and $PM_{2.5}$ (5 $\mu g/m^3$) – all annual means (World Health Organisation WHO, 2021). These guidelines are global guidance rather than representing a "safe" value. These pollutants are monitored, to a greater or lesser extent, by a network of sensors worldwide (World's Air Pollution). Some urban environments have shown pollution values orders of magnitude higher values than the guideline values. For example, Moradabad in India has had PM_{10} values of 999 $\mu g/m^3$ (indeed the real value may be higher than this, three digits being the limit to the display) and Baoding in China has had $PM_{2.5}$ as high as 900 $\mu g/m^3$ (Huang et al., 2018). With respect to NO_2, New Delhi has reported levels as high as 233 $\mu g/m^3$ (Nandi, 2018), and values as high as 500 $\mu g/m^3$ have been reported elsewhere (Jarvis et al., 2010). These are not historic levels, at the time of writing (15:00 GMT, 17th June 2022) Arrecife, Canarias, Spain has a $PM_{2.5}$ value of 754 $\mu g/m^3$ and Sama, Asturias, Spain has a PM_{10} value of 883 $\mu g/m^3$. Suffice it to say, some places in the world can have extremely poor air quality for short periods of time, and this affects all regions of the world. However, even recent annual averages of $PM_{2.5}$ in some cities can exceed 100 $\mu g/m^3$ (Rodríguez-Urrego and Rodríguez-Urrego, 2020).

Historically, motor vehicles have contributed substantially to global air pollution, with their contribution estimated to be between 4 and 40% of the total, depending on the pollutant and location, 10–20 years ago (McCubbin and Delucchi, 1999; Wang et al., 2009). Key pollutants from internal combustion engine vehicles (ICEVs) that are a concern from

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ambient air pollution are NO_x, PM, hydrocarbons, CO, and trace amounts of others. Together these are known as pollutant emissions (sometimes referred to as criteria pollutants).

Recognising this, government and industry have been working on reducing emissions from vehicles for decades and today, tailpipe emissions from modern vehicles contribute very little to total ambient air pollution in many places (Air Quality Expert Group AQEG, 2019). Indeed, modern ICEVs can emit very low levels of all of the pollutants of concern thanks to aftertreatment devices including catalyst technologies (for gaseous emissions) and particulate filters (for particulate matter) (Kasab and Strzelec, 2020). Some vehicles have even been shown to emit levels which are indistinguishable from zero, as measured by the most accurate instrumentation available (ADAC, 2019). This has been driven by strict emissions legislation worldwide, with PM emissions being regulated to values of 4.5 mg/km (Euro 6d), 3 mg/km (China 6), and 3 mg/mile (Tier 3, USA) and NO_x emissions being regulated to values of 60 mg/km (Euro 6d), 35 mg/km (China 6), and 20 mg/mile (Tier 3).

It has not always been the case that vehicles emitted these certification values in real-world use. The dieselgate scandal shone a spotlight on this (Senecal and Leach, 2021). However, since 2017, European emissions legislation, and since 2020 Chinese emissions legislation (to pick two examples) have required so-called real driving emissions (RDE) as part of vehicle certification. The details vary, but emissions from a vehicle are measured in use on a road (as distinct from in a laboratory) using a portable emissions measurement system (PEMS) with all of the uncertainties that come from traffic and other real-world factors. These tests are conducted over different types of driving, typically including some city driving (urban), some rural driving, and some motorway (highway) driving (Mock, 2017). RDE measurements may not be undertaken as part of a certification test, independent providers also undertake tests on-road at a wider range of conditions than certification requires, and the results are widely reported (ADAC, 2019; Molden, 2022).

Of course, these mg/km values, whether certification or RDE, are not emitted constantly by a vehicle, these values represent an average. Vehicle emissions in practice are dictated by, amongst other things, the engine speed and load (which are a function of how the vehicle is driven) and the temperature of the aftertreatment systems and vary transiently along a journey (Duckhouse et al., 2018; Leach et al., 2020). Depending on the length of a journey, a substantial portion of emissions are emitted during the cold-start phase (where the engine and aftertreatment systems are not yet at their operating temperatures) (Stone, 2012).

Recognising these low emissions values both in the legislation and real-world operation today, there is a vision for so-called zero-impact emissions from ICEVs; zero-impact describing the pollutant emissions as distinct from greenhouse gases such as CO_2. Such vehicles would have zero measurable pollutant emissions at their tailpipe. This has led to claims that, therefore, ICEVs would "clean the air" – by emitting zero pollutant emissions at their tailpipe they would inevitably emit less than the air at the intake to the vehicle (Reitz et al., 2020; Pischinger, 2020).

Previous work has explored the concept by using catalysed radiators to see whether atmospheric ozone could be reduced by vehicles (Oh et al., 1998). However, Oh et al. concluded that atmospheric ozone concentrations at roadside and flow rates through the radiator were insufficient to achieve this. Although this illustrates the challenge of obtaining sufficient flow rates through a catalyst (whether mounted in the radiator or in the tailpipe as in this work), it is not a perfect comparison as unlike particulate matter and NO_x, ozone is not emitted from vehicle tailpipes in meaningful concentrations, so there is no chance of reducing an exhaust plume from the preceding vehicle with ozone.

A completely different approach to this question was explored by Wallington et al. (2022). They compared the 2020 fleet exhaust emissions concentrations (on average) to National Ambient Air Quality Standards (NAAQS) atmospheric pollutant values and found that for NO_2 and $PM_{2.5}$ undiluted exhaust emissions concentrations were on average 150 and 220 times higher (respectively) than atmospheric concentrations.

This work, then, seeks to explore the conditions under which it might be possible for a modern ICEV to emit less of a pollutant than the concentration of that pollutant in the air that it breathes. In other words, can an internal combustion engine clean the air? The pollutant emissions particulate matter and NO_x will be considered due to the widespread availability of atmospheric data for these pollutants. Accuracy of instrumentation measuring tailpipe emissions of particulate matter and NO_x will be considered, alongside conversions between ambient air pollution measurements (of NO_2, PM_{10}, and $PM_{2.5}$) and mass of pollutants exiting vehicle exhausts under different conditions. Exhaust plumes subject to atmospheric dilution will also be considered, for cases where vehicles may be breathing air emitted from a vehicle travelling ahead of it. This will capture both the average behaviour from the certification RDE values and the transient plume behaviour as far as the available data will allow.

2. Methodology

Key to establishing whether an ICEV is emitting less of a particular pollutant than it is drawing in is determining the mass of a particular pollutant that the ICEV intakes and emits over its operation. All global legislation regarding pollutant emissions from light duty vehicles is expressed in the mass (or sometimes number in the case of PM emissions) of the pollutant emitted per unit of distance travelled (Senecal and Leach, 2021). For example, the Euro 6d legislation specifies a NO_x emission maximum of 60 mg/km when tested over various emission cycles, and 85.8 mg/km under real driving conditions (a conformity factor of 1.43 on the cycle value). Given the commonality of measuring emissions per unit of distance travelled (rather than per unit time or per unit energy or power) this is what will be adopted in this work.

Therefore, key to answering the question "can an internal combustion engine clean the air" is the relative concentrations of pollutant between the intake and exhaust of an ICEV. In order to determine this, the flow rate of (inlet/exhaust) gas per km the vehicle travels is needed, alongside the relative concentrations of the pollutants in those gas streams.

In order to determine the mass flow rate of pollutant into the engine per km, the following method is adopted. The distance that the vehicle travels per engine revolution is determined from the tyre circumference (T) and the gear ratio (R). Then the volume of air inlet per km is determined from the engine capacity (V), the distance that the vehicle travels per engine revolution divided by two (because a four-stroke engine is assumed), and the volumetric efficiency (η_v). This can then be combined with the inlet air pollutant concentration (C - usually express as mass per unit volume) to obtain the mass flow rate of pollutant into the engine per km. This is shown in Equation (1).

$$\textit{Mass of pollutant inlet per km} = \frac{1000}{T} \times \frac{R}{2} \times V \times \eta_v \times C \quad (1)$$

The mass flow rate of pollutant out of the engine per km is more straightforward to obtain. This value could be based on emissions legislation (such as the Euro 6d NO_x value of 60 mg/km). Alternatively it could be based on Real Driving Emission (RDE) values obtained experimentally. When using the latter, it is sensible to include an assessment of the accuracy which the instrumentation can measure such emissions, as the values can be very low – indeed as low as "zero" (ADAC, 2019) as measured within the accuracy of the instrument. Clearly if a vehicle actually emits zero of a pollutant, then the inlet:outlet pollutant ratio will be infinite and the ICEV will eliminate all the pollution that it takes in.

Fig. 1 shows a flowchart of the methodology adopted in this work. The assessment of whether the an ICEV is emitting less of a particular pollutant than it is drawing in is made by determining the inlet:outlet pollutant ratio. If its value is less than one, the ICEV is emitting more

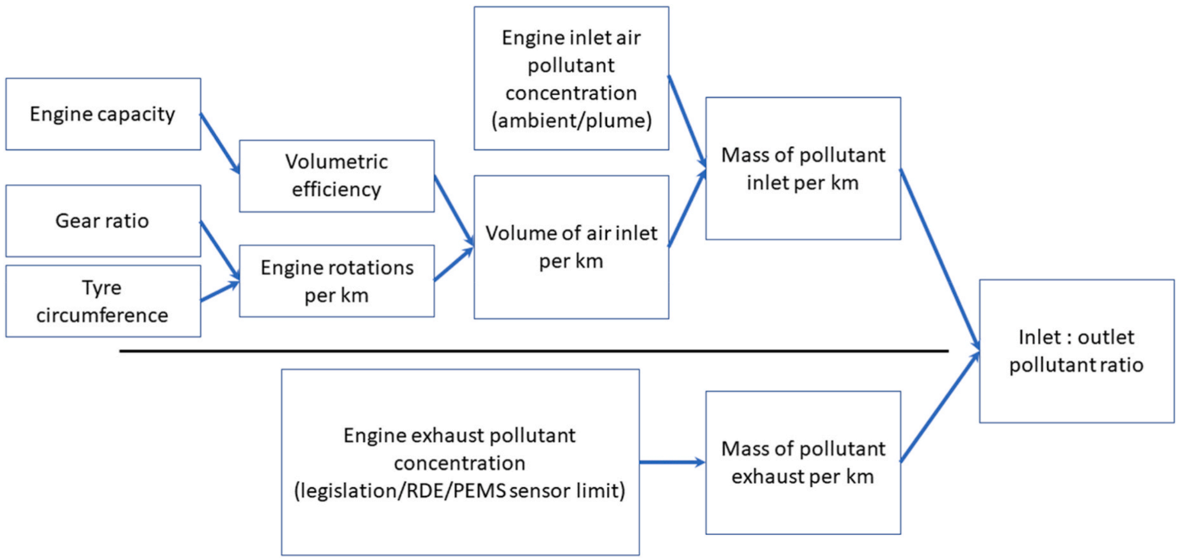

Fig. 1. Overview of methodology for determining inlet:outlet pollutant ratio.

than it is taking in, and if its value is greater than one the ICEV is emitting less than it is taking in – i.e. it is acting as a pollution reduction device for that pollutant.

2.1. Selection of values

It is clear that there are a huge range of values that all of these parameters could take, and the author encourages interested readers to make their own choices. Typical ambient air pollution concentrations are measured of order parts per billion (ppb) (Bush et al., 2022) and typical vehicle emissions are measured of order parts per million (ppm) (Leach et al., 2020), three orders of magnitude difference. Therefore, as a starting point, two cases are considered, a typical case, and an extreme case – the extreme case designed to give the ICEV as good as possible chance at emitting less pollutant emissions than it takes in. However, clearly if a vehicle is stationary, it would intake an infinite amount of air per km, so the assumption is that a vehicle is moving – however slowly. It is observed that the case of interest is one where the emissions from the ICEV are zero, or near-zero, and the ambient air being drawn into the engine is very polluted. Clearly there are many cases where the reverse is true, and these are not irrelevant, rather – as will be seen from the results – the instances where an ICEV can emit less than ambient are so limited, that these cases are not presented.

2.1.1. Vehicle parameters

The input parameters to the model concerning the vehicle are tyre circumference, gear ratio, and engine capacity. Clearly there are thousands of different models of ICEV on sale so picking a typical case is subjective. Nevertheless, for this purpose a 2022 model Vauxhall Corsa Design 1.2 (75 PS) vehicle (marketed outside the UK as an Opel Corsa) has been selected on the basis that it is the bestselling ICEV in 2022 to date in the UK (SMMT, 2022), and data are readily available (Corsa Price and Specification Guide, 2022). This particular model is fitted with 195/55 R 16 tyres, and a 1.2 L engine. It is assumed for the typical case that the vehicle is travelling in 4th gear – equivalent to, say, driving at 30 mph in an urban environment. The choice of volumetric efficiency is again extremely subjective, without access to the engine in a laboratory test-cell environment. However, the engine is fitted with a variable valve train, and so a generous value here might be 40%.

For the extreme case, the aim is to maximise the inlet air flow rate through the ICEV per km travelled, so the assumption will need to be a small tyre, vehicle in first gear, and a large capacity engine. Again, there is enormous scope for variation, but the Bugatti Chiron has a high first gear ratio, a large capacity engine (8 L), and is fitted with 285/30 R 20 tyres. Although turbo/supercharging would improve the air flow through the ICEV, it is unlikely that a vehicle travelling sufficiently slowly would be operating turbo/supercharged beyond 100% volumetric efficiency. It is slightly counterintuitive to think that the high engine capacity supercar is the vehicle which is more likely to reduce pollution, but remember at this stage the aim is to maximise the inlet flow through the engine, rather than comment on how efficient its exhaust aftertreatment system is.

The parameters input are for both cases are shown in Table 1.

2.1.2. Inlet air pollutant concentration

A selection of inlet air pollutant concentrations have been selected to test in this work, these include some very high values measured worldwide, the WHO guideline exposure values, and estimated vehicle plume values. The latter are values that might be expected to be the inlet concentration if a vehicle was following closely behind a preceding vehicle. Clearly if the exhaust of the vehicle in front were physically connected (leak free) to the vehicle behind then outlet concentrations could be equal to inlet. However, this is clearly unrealistic. However, a limited set of values exist in the literature for diluting plume values downstream of a vehicle, and these can be used, representing some of the transient emissions values that are possible from vehicles. The inlet air pollutant concentration values considered in this work are shown in Table 2 (NO_2) and Table 3 (PM).

2.1.3. Vehicle pollutant emission concentration

There is almost infinite possible variation in ICEV emissions, however in this work four cases are considered both for NO_2 and PM. The two most common emissions legislation values globally (at the time of writing) that use RDE in part for certification testing – Euro 6d and China 6. The USA standards (Tier 3), which are also very common, do not use an RDE component. As such, direct relationships between ambient air quality and the real emissions from a vehicle certified under

Table 1
Vehicle parameter values for typical and extreme cases.

	Typical case	Extreme case
Tyre circumference (m)	1.95	2.20
Gear ratio (–)	1.121 (fourth gear)	10 (first gear)
Engine capacity (L)	1.199	7.998
Engine volumetric efficiency (%)	40	100

Table 2
Inlet NO_2 concentration values considered in this work.

	NO_2 (µg/ m^3)	Source
Beijing, China, 2013	120	Cheng et al. (2018)
London, UK, 2014	463	Griffiths (2014)
Delhi, India, 2015	233	Nandi (2018)
WHO 24-h exposure guideline	25	World Health Organisation WHO (2021)
WHO annual mean exposure guideline	10	World Health Organisation WHO (2021)
Plume 1 from preceding vehicle[a]	2927	Janssen and Hagberg (2020)
Plume 2 from preceding vehicle[a]	1250	Tajdaran et al. (2022)

[a] These plumes will be comprised of NO_x rather than NO_2, but are treated as NO_2.

Table 3
Inlet PM concentration values considered in this work.

	PM (µg/ m^3)	Source
Moradabad, India, 2020 ($PM_{2.5}$)	999	World's Air Pollution
Baoding, China, 2015 ($PM_{2.5}$)	900	Huang et al. (2018)
Sama, Asturias, Spain, 2022 (PM_{10})	883	World's Air Pollution
WHO 24-h exposure guideline (PM_{10})	45	World Health Organisation WHO (2021)
WHO annual mean exposure guideline (PM_{10})	15	World Health Organisation WHO (2021)
WHO 24-h exposure guideline ($PM_{2.5}$)	15	World Health Organisation WHO (2021)
WHO annual mean exposure guideline ($PM_{2.5}$)	5	World Health Organisation WHO (2021)

Tier 3 are not clear, so it is omitted from this study. Euro 6d and China 6 provide average values over the distance the vehicle is driven. In addition a low RDE value measured from a large Transport for London portable emissions measurement system (PEMS) study (Transport for London, 2014) and the maximum possible emitted value when a correctly functioning PEMS is reading zero (i.e. its measurement accuracy). These values are shown in Table 4 (NO_2) and Table 5 (PM).

Emissions of NO_x from ICEVs consist both of NO and NO_2. Generally, NO_2 makes up less than 10% of total NO_x in vehicle exhausts (Heywood, 2018), but this can vary and may be substantially higher (>50%) for short time periods (Leach et al., 2021a). For vehicles (usually diesels) fitted with Selective Catalytic Reduction (SCR) aftertreatment, the preferable NO:NO_2 ratio is around 50:50 (Senecal and Leach, 2021) and so NO_x emissions from these vehicles will often be closer to that ratio. For a given vehicle then, it is unknown what the NO:NO_2 ratio in the exhaust is. However, NO generally oxidises further to NO_2 in the atmosphere in a timescale of order hours (Leach et al., 2021b). Furthermore, atmospheric measurements of NO are rare, even at roadside, but measurements of NO_2 are widespread. Therefore, although the actual emission will not be all NO_2, the medium-long term chemical impact on the atmosphere will be in the form of NO_2. For this reason, the NO_x concentration values in the exhaust are treated as all NO_2 in this work (and this is true for the plume value displayed in Table 2).

Table 4
Vehicle exhaust NO_2 concentration values considered in this work.

	NO_2 (mg/ km)	Source
Euro 6d	60	Senecal and Leach (2021)
China 6	35	Senecal and Leach (2021)
Best RDE	1	Transport for London (2014)
"Zero" (as defined by the accuracy of the PEMS)	23.8 (µg/ km)	Weiss et al. (2011)

Table 5
Vehicle exhaust PM concentration values considered in this work.

	PM (mg/ km)	Source
Euro 6d	4.5	Senecal and Leach (2021)
China 6	3.0	Senecal and Leach (2021)
Best RDE	0.3	Transport for London (2014)
"Zero" (as defined by the accuracy of the PEMS)	5 (µg/km)	Oberguggenberger et al. (2012)

A spreadsheet tool incorporating calculations of inlet:outlet pollutant ratio using the example values discussed in this work is available and a link to obtain it is included in the supplementary data section of this paper.

3. Results and discussion

3.1. NO_2

Table 6 and Table 7 show the inlet:outlet NO_2 ratios for the inlet and outlet scenarios presented in Tables 2 and 4 respectively for the typical (the Vauxhall Corsa) and extreme (the Bugatti Chiron) cases. For the typical case it can be seen that under no circumstances can the ICEV meet the WHO guideline exposure values, however, if the PEMS equipment is reading zero NO_x being emitted from the ICEV, then it will be emitting less NO_2 than the concentration of NO_2 in the inlet when driving through the most polluted value available (London in 2014), and when the inlet air is a representative exhaust plume from a gross emitter – i.e. under these circumstances it is possible for the ICEV to clean the air of NO_2.

For the extreme case (Table 7), when the PEMS reads zero, the ICEV will always clean the air of NO_2, however even for the extreme case, which is very unlikely to occur in practice, the ICEV will never clean the air on average if it merely meets the Euro 6d standards (this does not mean that transiently such a vehicle might under certain conditions). In addition, even in the extreme case, not even the best-in-class RDE data (save that of "zero") will meet the WHO exposure guidelines for NO_2.

3.2. Particulate matter

Table 8 and Table 9 show the inlet:outlet PM ratios for the inlet and outlet scenarios presented in Tables 3 and 5 respectively for the typical and extreme cases. For the typical case, it can be seen that when the PEMS equipment is reading 0 p.m. being emitted, then it will be emitting less PM than the concentration of PM in the inlet when driving through the most polluted air (Moradabad in 2020) and the ICEV can exceed the WHO guideline 24-h exposure value for PM_{10} under those circumstances as well. However, under all other exhaust conditions, the ICEV never emits less PM than the inlet air value. The ICEV can also never meet the WHO annual mean exposure guidelines or the 24-h exposure target for $PM_{2.5}$.

For the extreme case (Table 9), when the PEMS reads zero, the ICEV will always clean the air of PM, and, for the most polluted cities (such as the Moradabad, 2020 example used here) the ICEV will also always, on average, clean the air of PM provided it is certified at least to the Euro 6d standard. However, even considering this is the extreme case, not even the best-in-class RDE data (save that of "zero") or any other certification standard will, on average, meet the WHO exposure guidelines for PM (save the best RDE vehicles which will meet the WHO 24-h exposure guideline for PM_{10}. That any ICEV certified at least to the Euro 6d standard will, on average, clean the air of PM in the most polluted cities in the world is indicative of two things, firstly that modern ICEVs fitted

Table 6
Inlet:outlet NO_2 ratio for various inlet and outlet scenarios for the typical case. Highlighted cells indicate where the ICEV acts as a NO_2 reduction device.

Inlet\Exhaust	Euro 6d	China 6	Best RDE	"Zero" as measured by PEMS
Plume 1	0.01	0.01	0.40	16.95
Plume 2	0.00	0.00	0.17	7.24
London, UK, 2014	0.00	0.00	0.06	2.68
WHO 24-hour exposure guideline	0.00	0.00	0.00	0.14
WHO annual mean exposure guideline	0.00	0.00	0.00	0.06

Table 7
Inlet:outlet NO_2 ratio for various inlet and outlet scenarios for the extreme case. Highlighted cells indicate where the ICEV acts as a NO_2 reduction device.

Inlet\Exhaust	Euro 6d	China 6	Best RDE	"Zero" as measured by PEMS
Plume 1	0.89	1.52	53.20	2235.03
Plume 2	0.38	0.65	22.72	954.49
London, UK, 2014	0.04	0.06	2.18	91.63
WHO 24-hour exposure guideline	0.01	0.01	0.45	19.09
WHO annual mean exposure guideline	0.00	0.01	0.18	7.64

Table 8
Inlet:outlet PM ratio for various inlet and outlet scenarios for the typical case. Highlighted cells indicate where the ICEV acts as a PM reduction device.

Inlet\Exhaust	Euro 6d	China 6	Best RDE	"Zero" as measured by PEMS
Moradabad, India, 2020 ($PM_{2.5}$)	0.03	0.05	0.46	27.54
WHO 24-hour exposure guideline (PM_{10})	0.00	0.00	0.02	1.24
WHO annual mean exposure guideline (PM_{10})	0.00	0.00	0.01	0.41
WHO 24-hour exposure guideline ($PM_{2.5}$)	0.00	0.00	0.01	0.41
WHO annual mean exposure guideline ($PM_{2.5}$)	0.00	0.00	0.00	0.14

Table 9
Inlet:outlet PM ratio for various inlet and outlet scenarios for the extreme case. Highlighted cells indicate where the ICEV acts as a PM reduction device.

Inlet\Exhaust	Euro 6d	China 6	Best RDE	"Zero" as measured by PEMS
Moradabad, India, 2020 ($PM_{2.5}$)	4.04	6.05	60.53	3631.82
WHO 24-hour exposure guideline (PM_{10})	0.18	0.27	2.73	163.60
WHO annual mean exposure guideline (PM_{10})	0.06	0.09	0.91	54.53
WHO 24-hour exposure guideline ($PM_{2.5}$)	0.06	0.09	0.91	54.53
WHO annual mean exposure guideline ($PM_{2.5}$)	0.02	0.03	0.30	18.18

with particulate filters are exceptionally clean, and secondly, that the most polluted cities in the world are really very polluted (this example being 66 × the WHO recommended 24-h exposure guideline value for $PM_{2.5}$).

Non-exhaust PM emissions are not considered in this work, but it is noted that they are typically at least of order 2–3 × higher than the Euro 6d limit value (Senecal and Leach, 2021), and some studies have reported values as high as 1000 × (Emissions Analytics, 2022). Considering Tables 8 and 9 this would reduce the cases where the inlet:outlet pollution ratio was greater than one. Battery electric vehicles would also emit non-exhaust PM and, not having an engine and aftertreatment system to reduce the PM, would also have no significant capacity (beyond say the pollen filter for cabin air which is changed at much lower rates than the flow rate through an engine) to filter the ambient PM out of the air.

4. Conclusions

The fundamental question in this work is whether an internal combustion engine vehicle (ICEV) can emit less of a pollutant (NO_2 or PM) than the concentration of that pollutant in the air that it inlets. The answer is "yes", but only under certain circumstances. For a typical vehicle driving under typical urban conditions, such a reduction is only possible when the vehicle is either travelling through a plume emitted from a gross emitter travelling in front of it (NO_2) or when it is travelling through some of the most polluted air ever seen globally (PM). With a typical vehicle that is working well, such circumstances are only likely to be seen under cold-start conditions.

For an extreme case (a vehicle with a large engine travelling in first gear), such a "cleaning air" action is more likely, particularly when the vehicle is emitting zero as measured by state-of-the-art PEMS systems, a standard which some ICEVs today already meet. However, it must be stressed that this extreme case is very unlikely (the example used in this paper is a Bugatti Chiron which has only sold 500 units globally) and when it does occur, it will be for very short durations, rather than sustained.

This work only deals with average values, as they are what are most commonly measured and available in the literature. However, it would be possible to make simultaneous pollutant concentration measurements in the intake air and the exhaust. These, if conducted with fast-response instrumentation, would provide a good indication of when and where a vehicle is "cleaning the air" transiently.

Overall, modern ICEVs are very clean with regards to pollutant emissions, but if it is desired that they can clean air to within WHO guideline exposure values then emissions aftertreatment systems will need to become cleaner than they are today and the accuracy of PEMS instrumentation will also need to be improved.

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CRediT authorship contribution statement

Felix Leach: Conceptualization, Methodology, Data curation, Funding acquisition, Investigation, Visualization, Writing – original draft, preparation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Felix Leach reports financial support was provided by Natural Environment Research Council.

Data availability

Data is available in the supplementary material

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2022.119488.

Nomenclature

CO	Carbon monoxide
ICEV	Internal combustion engine vehicle
NO_x	Oxides of nitrogen
PEMS	Portable emissions measurement system
PM	Particulate matter
$PM_{2.5}$	Fraction of PM where particles are less than 2.5 μm in diameter
PM_{10}	Fraction of PM where particles are less than 10 μm in diameter
RDE	Real driving emissions
SCR	Selective catalytic reduction
WHO	World Health Organisation

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