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Review article

Non-exhaust PM emissions from electric vehicles

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HIGHLIGHTS

- A positive relationship exists between vehicle weight and non-exhaust emissions.
- Electric vehicles are 24% heavier than their conventional counterparts.
- Electric vehicle PM emissions are comparable to those of conventional vehicles.
- Non-exhaust sources account for 90% of PM_{10} and 85% of $PM_{2.5}$ from traffic.
- Future policy should focus on reducing vehicle weight.

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ABSTRACT

Particulate matter (PM) exposure has been linked to adverse health effects by numerous studies. Therefore, governments have been heavily incentivising the market to switch to electric passenger cars in order to reduce air pollution. However, this literature review suggests that electric vehicles may not reduce levels of PM as much as expected, because of their relatively high weight. By analysing the existing literature on non-exhaust emissions of different vehicle categories, this review found that there is a positive relationship between weight and non-exhaust PM emission factors. In addition, electric vehicles (EVs) were found to be 24% heavier than equivalent internal combustion engine vehicles (ICEVs). As a result, total PM_{10} emissions from EVs were found to be equal to those of modern ICEVs. $PM_{2.5}$ emissions were only 1–3% lower for EVs compared to modern ICEVs. Therefore, it could be concluded that the increased popularity of electric vehicles will likely not have a great effect on PM levels. Non-exhaust emissions already account for over 90% of PM_{10} and 85% of $PM_{2.5}$ emissions from traffic. These proportions will continue to increase as exhaust standards improve and average vehicle weight increases. Future policy should consequently focus on setting standards for non-exhaust emissions and encouraging weight reduction of all vehicles to significantly reduce PM emissions from traffic.

1. Introduction

Air quality is a large concern in Europe. According to the European Environmental Agency (EEA), PM is one of Europe's most problematic pollutants in terms of harm to human health, being responsible for several hundreds of thousands of premature deaths in the European Region every year (European Environmental Agency, 2014).

Traffic is one of the main reasons why PM levels are too high, and is the primary source of PM in urban areas (Charron et al., 2007; Kousoulidou et al., 2008; Pant and Harrison, 2013). Vehicles emit PM through their exhaust and through non-exhaust sources, such as tyre wear, brake wear, road surface wear and resuspension of road dust (Thorpe and Harrison, 2008).

PM is often divided into PM_{10} and $PM_{2.5}$, which represent particles with a diameter of less than 10 μm and 2.5 μm, respectively. The link between exposure to PM and adverse health effects has been well documented (European Environmental Agency, 2014; Valavanidis et al., 2008; Li et al., 2003; Gehring et al., 2015; World Health Organisation, 2014; Sacks et al., 2010). However, the precise effects on health due to exhaust and non-exhaust emissions are less well understood.

Exhaust PM emissions are mainly made up of $PM_{2.5}$ and contain a variety of hydrocarbons, which can contribute to respiratory disease or lead to increased incidence of cancer (Kagawa, 2002).

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Non-exhaust emissions tend to contain mostly PM_{10}, but a significant proportion of the emissions contains fine $PM_{2.5}$ as well. The chemical characteristics of non-exhaust PM emissions vary per source, but are mainly made up of heavy metals such as zinc (Zn), copper (Cu), iron (Fe) and lead (Pb), among others (Thorpe and Harrison, 2008). There are several toxicological studies that have found links between non-exhaust emissions and adverse health effects, such as lung-inflammation and DNA damage (Cassee et al., 2013; Gasser et al., 2009; Gualtieri et al., 2005; Mantecca et al., 2009; Karlsson et al., 2006), and a review of epidemiological studies concluded that PM_{10} indeed has an effect on mortality (Brunekreef, 2005).

Because of the chemical differences between non-exhaust and exhaust emissions, they result in different secondary PM. Secondary PM is formed in the atmosphere through chemical reactions, rather than being directly emitted by a source. The volatile organic compounds in exhaust gases react with sunlight in the atmosphere to form secondary organic aerosols (SOAs) whereas non-exhaust emissions are mainly inorganic and therefore form secondary inorganic aerosols (SIAs). However, it is exceedingly difficult to model SOAs and SIAs emissions (Hoogerbrugge et al., 2015; Air Quality Expert Group, 2012). Not only do many studies have difficulty determining the fractional contribution vehicles make to SOAs, but it is also problematic to differentiate between primary and secondary PM (Amato et al., 2013; Viana, 2011; Bahreini et al., 2012). Therefore, there is always the risk of double-counting PM (Humbert et al., 2015). SOAs may have a significant influence on PM levels. However, more research is needed to determine their relative importance. The largest part of the non-exhaust emissions is resuspended PM, possibly including secondary PM emissions. For that reason we have not differentiated between primary and secondary PM emissions.

One of the strategies being adopted in many European countries to improve air quality is incentivising the electrification of passenger cars (EAMA, 2015; Mock and Yang, 2014). The switch to EVs has been proposed as a solution to air pollution, offering zero emissions and promising cleaner air for everyone (Dutch Government, 2011; EU, 2005; Murrells and Pang, 2013). However, when modelling the impact of EVs on air quality, Soret et al. (2014) found that fleet electrification would not significantly reduce PM emissions due to the importance of non-exhaust emissions.

This literature review attempts to investigate this further by determining the weight difference between EVs and ICEVs, quantifying the impact this has on non-exhaust emissions and finally comparing the total PM emissions from EVs and ICEVs. It is important to note that this literature review is only concerned with the PM emissions from EVs and ICEVs. A complete understanding of the value of EVs versus ICEVs is beyond the scope of this study.

2. Weight and emission

2.1. Hypothesised influence of weight

It can be hypothesised that each of the sources of non-exhaust PM emissions should be influenced by vehicle weight.

We know that road abrasion and tyre wear are caused by the friction between the tyre thread and road surface. Friction is a function of the friction coefficient between the tyres and the road, as well as a function of the normal force of the road. This force is directly proportional to the weight of the car. This means that increasing vehicle weight would increase the frictional force and therefore the rate of wear on both the tyre and road surface.

Brake wear is caused by the friction between the brake pads and the wheels. The energy needed to reduce the momentum of a vehicle is proportional to the vehicle's speed and mass. Therefore, as the mass of the vehicle increases, more frictional energy is needed to slow it down, leading to greater brake wear.

Resuspension is caused by the wake of a vehicle, which in turn is determined by the size, weight and aerodynamics of the vehicle. Furthermore, heavier vehicles are able to grind down larger particles into smaller, more easily suspended PM. In addition, many heavier vehicles will also be larger, resulting in a larger wake. These factors together should cause increased resuspension.

2.2. Evidence for influence of weight

In his paper, Simons (2013) presented new and updated datasets for emissions of passenger cars. He distinguishes between vehicle exhaust and non-exhaust emissions and is one of the first to define non-exhaust emissions as a factor of vehicle weight, with the intention of being applied to studies on hybrid and electric vehicles. Simons suggests that PM_{10} emission factors could be scaled directly to vehicle weight and provides emission factors for tyre, brake and road wear per kg of vehicle weight. For example, tyre, brake and road wear increase by around 50% when comparing a medium (1600 kg) and small (1200 kg) car. Compared to a small car, large cars (2000 kg) emitted more than double the amount of PM_{10}. See Fig. 1.

There is very little other research that directly links non-exhaust PM emissions to vehicle weight. Some authors have speculated about the possible influence of weight, but not directly measured it. Barlow (2014) mentions that vehicle weight is likely to be one of the factors affecting tyre wear. He also says that in general, larger vehicles produce larger non-exhaust emissions. These assertions are only explained qualitatively, however. Similarly, Garg et al. (2000) mention that the inertia weight being stopped is one of the factors contributing to brake wear rate, but does not perform any tests with varying weights to confirm this.

Despite the lack of direct research, there is significant indirect evidence for the positive relationship between weight and non-exhaust PM emissions. Many studies and emission inventories suggest that heavier vehicle categories emit more PM.

The European Environmental Agency (EEA) publishes an Emission Inventory Guidebook (Ntziachristos and Boulter, 2013) which provides emission factors for different vehicle types. In this emission inventory, passenger cars are defined as vehicles carrying up to nine passengers, whereas light duty vehicles (LDVs) are defined as vehicles with a gross weight of up to 3500 kg. LDV emission factors of total suspended particles (TSP), PM_{10} and $PM_{2.5}$ were 57% higher than those of passenger cars for both tyre and brake wear, but road surface wear was the same for both.

The U.S. Environmental Protection Agency (EPA) (2014) has their own emission inventory called MOVES2014, which contains

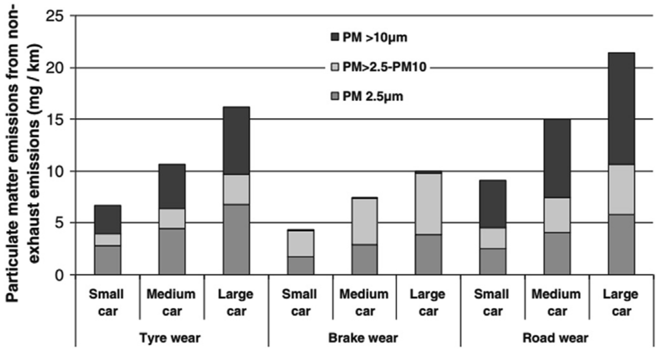

Fig. 1. Non-exhaust PM emissions by source and car size, from Simons (2013) based on Ntziachristos and Boulter (2009).

emission factors for tyre and brake wear. They distinguish between passenger cars (<2720 kg) and passenger trucks (<3855 kg), and assert that the latter emit 67% more PM_{10} and $PM_{2.5}$ due to brake wear but only 2% more due to tyre wear.

The Pollutant Release and Transfer Register in The Netherlands (PRTR) provide their own emission inventory with emission factor estimates for tyre wear (ten Broeke and Hulskotte, 2008) based on extensive research. They consider the average empty weight of a passenger car to be 850–1050 kg and the gross weight of a van to be around 2000 kg. They suggest that the total tyre wear, PM_{10} and $PM_{2.5}$ emissions were 40% higher for vans compared to regular passenger cars. The PRTR also has a report on calculating emissions per tyre for different vehicle categories (Klein et al., 2014). In this report, wear rate per tyre is 10% higher for passenger cars than for motorcycles, 20% higher for delivery vans than for passenger cars and 130% higher for lorries than for passenger cars.

Several individual studies measuring non-exhaust emissions differentiate between passenger cars and LDVs. Despite varying definitions for the weight of vehicle categories, the general consensus is that LDVs emit more PM than passenger cars (Lükewille et al., 2001). For example, Garben et al. (1997) found tyre wear of LDVs to be 75% higher than that of passenger cars. Similarly, Gebbe et al. (1997) found tyre wear for LDVs to be more than twice that of passenger cars. BUWAL (2001) found that the PM_{10} emissions of passenger cars' brakes were twice as much as those from motorcycles. LDVs on the other hand, emitted over two and a half times more PM_{10} than passenger cars. Research by Garg et al. (2000) distinguishes between brake emissions from small cars, large cars and large pickup trucks. They found that the brakes of large cars emit 55% more TSP, PM_{10} and $PM_{2.5}$ than small cars. Large pickup trucks were found to emit more than double the amount of particulates compared to small cars.

Very little data is available on resuspension of road dust for different vehicle categories. Gillies et al. (2005) investigated emissions of vehicles on unpaved roads and found that emissions had a strong linear relationship with not only vehicle speed but also vehicle weight. The EPA's AP42 Method (Environmental Protection Agency, 2006) for estimation of resuspension includes a factor based on vehicle weight to the power 1.02, suggesting resuspension increases almost linearly with weight. This is in line with the results from a study by Amato et al. (2012) which used the same vehicle categories as the EPA (2014) and found that PM_{10} resuspension rates were 10 times higher for passenger cars than for motorcycles, and 3–4 times higher for LDVs than for passenger cars. See Table 1 for an overview of the results.

2.3. Weight comparison of electric and conventional passenger cars

In order to determine the additional non-exhaust emissions that EVs produce, a comparison must be made between the weight of EVs and ICEVs. The best way to do this is by determining the difference in weight between a highway-capable EV and its equivalent non-electric version. For example, the Ford Focus Electric and gasoline-powered Ford Focus hatchback have almost exactly the same specifications. The Electric, however is 219 kg heavier. The same applies to the Honda Fit: the electric version is 335 kg heavier than the conventional version. The Kia Soul EV is 311 kg heavier than the regular Kia Soul, etc. See Table 2 for the complete list. On average, the electric versions are 280 kg or 24% heavier than their ICE counterparts.

It is important to note that comparing electric vehicles and their conventional counterparts is not entirely straightforward. For example, the weight of the body of electric vehicles is often reduced significantly by using aluminium instead of steel to improve the range of the vehicle (Nealer and Hendrickson, 2015). If this would be done with conventional cars, the weight difference would be even greater than it already is. Furthermore, EVs have many limitations that ICEVs do not have. For example, the Volkswagen e-Golf has a top speed of 140 km/h, a range of 133 km and cannot carry any trailer load. The Volkswagen Golf on the other hand, has a top speed depending on engine size between 179 and 203 km/h, a range of over 1000 km and can carry a trailer load up to 1100 kg. This all makes direct comparison problematic, especially since only limited data on vehicle specifics is publicly available.

Very few other studies compare the weight of vehicles by their power train technology. Bauer et al. (2015) used a simulation of a mid-size vehicle to compare the weight of ICEVs and EVs in 2012 and projected in 2030. They found that in 2012, ICEVs were 1567 kg on average, whereas EVs were 1944 kg (24% heavier). The projected values for 2030 were 1383 kg and 1613 kg for ICEVs and EVs, respectively.

2.4. Expected effect on emissions of EVs

More research is needed to determine the exact relationship between weight and non-exhaust emissions, but a reasonable estimate can be made using existing research. Based on the research by Simons (2013) an increase in weight of 280 kg will result in a PM_{10} increase of 1.1 mg per vehicle-kilometre (mg/vkm) for tyre wear, 1.1 mg/vkm for brake wear and 1.4 mg/vkm for road wear. For $PM_{2.5}$, these values are 0.8 mg/vkm, 0.5 mg/vkm and 0.7 mg/vkm for tyre, brake and road wear, respectively. However, brake wear of EVs tends to be lower because of their regenerative brakes (Barlow, 2014). There is very little literature which has investigated the actual reduction in emissions, so we have assumed a conservative estimate of zero brake wear emissions for EVs. For resuspension, it is reasonable to assume based on the research by Gillies et al. (2005) that there is a linear relationship between weight and resuspension, and therefore a 24% increase in resuspension is to be expected.

3. Exhaust and non-exhaust emission factors

In order to put this increase in emissions into perspective, the average PM_{10} and $PM_{2.5}$ emissions of passenger cars must be determined. As we know, passenger cars emit PM through exhaust and non-exhaust pathways.

3.1. Exhaust emissions

Before the introduction of air quality standards, exhaust emissions used to be a major source of PM, especially for diesel cars (Miguel et al., 1998). Since then, PM emission standards for vehicle exhausts have become increasingly strict and now all new diesel passenger cars are fitted with a diesel particulate filter (DPF). Bergmann et al. (2009) found that DPFs are very effective at reducing PM emissions, lowering the emitted mass of PM by 99.3%. This has resulted in greatly reduced particle emissions from diesels in the last ten years (Thorpe and Harrison, 2008; International Council on Clean Transportation, 2015).

The current instalment of European emission standards, EURO 6, dictates that new diesel and petrol cars must emit less than 5 mg/vkm to be allowed on the market (EU, 2007). It is expected that within the next decade, the majority of vehicles will comply with these regulations.

Many studies have been done to determine the amount of PM emitted by vehicle exhausts (Abu-Allaban et al., 2003; Gehrig et al., 2004; Bukowiecki et al., 2010; Lawrence et al., 2013; Luhana et al., 2004). Earlier studies tend to report higher emission factors than more recent ones, which is indicative of the improving exhaust

Table 1
Comparison of non-exhaust emissions for different vehicle categories.

Reference	Vehicle type	Non-exhaust source	Total wear (mg/vkm)	PM_{10} (mg/vkm)	$PM_{2.5}$ (mg/vkm)
Simons (2013)	Per vehicle kg	Tyres	0.0573	0.00408	0.00286
		Brakes	0.00445	0.00396	0.00174
		Road	0.00979	0.00490	0.00264
EEA (Ntziachristos and Boulter, 2013)	Passenger car	Tyres + Brakes	18.2 (s)	13.8	7.4
	Light duty truck	Tyres + Brakes	28.6 (s)	21.6	11.7
Dutch PRTR (ten Broeke and Hulskotte, 2008)	Passenger car	Tyres	100	5	1
	Van	Tyres	140	7	1.4
Dutch PRTR (Klein et al., 2014)	Motorcycle	per tyre	30 (u)/19 (r)	–	–
	Passenger car	per tyre	33 (u)/21 (r)	–	–
	Delivery van	per tyre	40 (u)/26 (r)	–	–
US EPA (2014)	Passenger car	Brakes	–	18.5	2.3
	Passenger truck	Brakes	–	30.9	3.9
	Passenger car	Tyres	–	6.1	0.9
	Passenger truck	Tyres	–	6.2	0.9
Garben et al. (1997)	Passenger car	Tyres	64	–	–
	LDV	Tyres	112	–	–
Gebbe et al. (1997)	Passenger car	Tyres	52.8	–	–
	LDV	Tyres	110	–	–
BUWAL (2001)	Motorcycle	Brakes	–	0.9	–
	Passenger car	Brakes	–	1.8	–
	LDV	Brakes	–	4.9	–
Garg et al. (2000)	Small car	Brakes	11.2/3.4 (s)	2.9	1.8
	Large car	Brakes	17.4/5.3 (s)	4.5	2.8
Amato et al. (2012)	Motorcycle	Resuspension	–	0.8–3.3	–
	Passenger car	Resuspension	–	9.4–36.9	–
	LDV	Resuspension	–	33.5–131.5	–

(s) = only includes suspended particles (u) = urban roads, (r) = rural roads.

Table 2
Comparison of weight between EVs and their ICEV counterparts, based on manufacturer information.

EV	ICEV	Mass in running order EV (kg)	Mass in running order ICEV (kg)	Weight difference (kg)	Weight difference (%)
Ford focus electric	Ford focus	1719	1500	+219	+14.6
Honda fit EV	Honda fit	1550	1215	+335	+27.6
Fiat 500e	Fiat 500	1427	1149	+278	+24.2
Smart electric drive coupe	Smart coupe	1055	820	+235	+28.7
Kia soul EV	Kia soul	1617	1306	+311	+23.8
Volkswagen e-Up!	Volkswagen Up	1289	1004	+284	+28.3
Volkswagen e-golf	Volkswagen golf	1617	1390	+227	+16.3
Chevrolet spark EV	Chevrolet spark	1431	1104	+327	+28.6
Renault fluence EV	Renault fluence	1618	1300	+318	+24.4

emission standards and higher measurement accuracy.

The most reliable indicators of emission factors are generally European and national emission inventories. These emission inventories compile data from vast amounts of measurements and studies to provide emission factors that can be used to estimate contributions to national air pollution. Moreover, emission inventories are revised every couple of years as new research becomes available.

One of these emission inventories is the EMEP/EEA Emission Inventory Guidebook (Ntziachristos and Samaras, 2013). This guidebook is used by EU countries to determine emissions from their vehicle fleets and report them annually to the EEA. The latest Emission Inventory Guidebook provides emission factors for different vehicles by fuel type, engine displacement and technology. The PM emission factors for gasoline and diesel passenger cars are generally very low, well below the EURO 6 limits.

Another emission inventory is available from the U.S. EPA (2008). For passenger cars, their model predicts that average exhaust emissions of both PM_{10} and $PM_{2.5}$ are much lower than the EURO 6 limit. Cai et al. (2013) used the EPA's Motor Vehicle Emission Simulator (MOVES) to estimate the exhaust PM emissions of passenger cars by model year. They found that exhaust emissions tend to decrease with newer models. Older gasoline cars emitted slightly more than the limits set by EURO 6, whereas newer models had much lower emission factors, on average. All diesel models with DPFs emit less than the EURO 6 limits, according to the computer model.

The Dutch PRTR (Klein et al., 2014) has exhaust emission factors in their emission inventory as well. For gasoline passenger cars, these are just below EURO 6 standards, whereas diesel vehicles with DPFs produce almost no emissions at all. This is in contrast with the UK national atmospheric emission inventory (NAEI) (Brown and Pang, 2014), which specifies that petrol cars emit almost no PM and diesel cars emit more than gasoline cars, depending on their engine technology. All of the reported emission factors for diesels are below EURO 6 limits.

If we average the suggested emission factors from theses emission inventories, we obtain a PM_{10} emission factor of 3.1 mg/vkm for gasoline cars and 2.4 mg/vkm for diesel cars. In terms of $PM_{2.5}$, these values were 3.0 mg/vkm and 2.3 mg/vkm for gasoline and diesel cars, respectively. Table 3.

3.2. Non-exhaust emissions

Numerous studies have investigated the non-exhaust emission factors of passenger cars. There are several ways to do this. The most common methods are:

Table 3
Exhaust emission factors for gasoline and diesel passenger cars.

Reference	Gasoline PM10 emissions (mg/km)	Gasoline PM2.5 emissions (mg/km)	Diesel PM10 emissions (mg/km)	Diesel PM2.5 emissions (mg/km)
US EPA (2008)	2.7	2.5	2.7	2.5
Cai et al. (2013)	4.7–6.4	4.3–5.9	3.1–4.7	3.0–4.5
EEA (Ntziachristos and Samaras, 2013)	1.1–2.2	1.1–2.2	1.5–2.1	1.5–2.1
Dutch PRTR (Klein et al., 2014)	4.0–5.0	4.0–5.0	1.0	1.0
UK NAEI (Brown and Pang, 2014)	1.0	1.0	1.6–3.2	1.6–3.2
Average	**3.1**	**3.0**	**2.4**	**2.3**

i) Estimation

Emission factors can be estimated based on national statistics of tyre use and brake use, average weight lost per tyre and brake, and average distance before a tyre/brake needs to be replaced. Some manufacturers also provide information on the rate of wear on tyres and brakes, which can be used to estimate emission factors. Examples of studies that use this method are those by Barlow (2014) and Legret and Pagotto (1999).

ii) Laboratory measurements

Laboratory measurements usually use a circular road simulator and weighted wheels, with or without brakes to test tyre, brake and road wear. Alternatively, tests can be done on a track in a wind tunnel to more closely simulate reality. Examples of studies which use a road simulator are Cadle and Williams (1978), Kupiainen et al. (2003, 2005), Garg et al. (2000), Dahl et al. (2006a, 2006b), Gustafsson et al. (2005, 2009), Sakai (1995) and Bukowiecki et al. (2009). Sanders et al. (2003). used a wind tunnel and track, while Chow et al. (1994) used a resuspension chamber to investigate the composition of road dust.

iii) Roadside and tunnel measurements

It is possible to calculate exhaust and non-exhaust emission factors by measuring PM levels near a road or at the inlet and outlet of a tunnel, comparing this to the background levels of PM and apportioning the difference to exhaust and non-exhaust sources by analysing the chemical composition of PM. Examples of tunnel studies are those by Lawrence et al. (2013) and Luhana et al. (2004). Roadside measurement studies were done by Bukowiecki et al. (2010), Johansson et al. (2004), Sjöberg and Ferm (2005), Abu-Allaban et al. (2003), Thorpe et al. (2007), Nicholson (2000) and Omstedt et al. (2005).

iv) Mobile on-board measurement

Mobile on-board measurement is done by attaching sampling devices directly onto a moving vehicle or in a trailer behind a moving vehicle. This type of study was performed by Fitz and Bufalino (2002), Bukowiecki et al. (2009) and Mathissen et al. (2012) and to determine resuspension emission factors.

Many of these studies find very different results, depending on the method of measurement, location and types of vehicles tested. Therefore, emission inventories from the EEA (Ntziachristos and Boulter, 2013), U.S. EPA (2014) Dutch PRTR (Klein et al., 2014; Denier van der Gon et al., 2008) and UK NAEI (Brown and Pang, 2014) analyse these studies to come up with the most representative emission factors for tyre wear, brake wear and road wear. Resuspension is currently only included in the UK emission inventory.

If we take the average results of these emission inventories, we obtain PM_{10} emission factors of 6.1 mg/vkm, 9.3 mg/vkm, 7.5 mg/vkm and 40 mg/vkm for tyre wear, brake wear, road surface wear and resuspension of road dust, respectively. $PM_{2.5}$ emissions are 2.9 mg/vkm, 2.2 mg/vkm, 3.1 mg/vkm and 12 mg/vkm for tyre wear, brake wear, road wear and resuspension, respectively. See Table 4. These results are in line with those found by the literature review of Grigoratos and Martini (2014).

4. Comparison EV and ICEV emissions

By using the data from Simons (2013) on the effect of weight on emissions and the average exhaust and non-exhaust emission from the various emission inventories, we can compare the total PM emissions from EVs with those from gasoline and diesel cars. When we do this, we find that EVs emit the same amount of PM_{10} as modern gasoline and diesel cars. See Table 5 for the comparisons.

When we compare $PM_{2.5}$ emissions, we can see that EVs bring about a negligible reduction in emissions. Compared to an average gasoline ICEV, the EV emits 3% less $PM_{2.5}$. Compared to an average diesel ICEV, the EV emits 1% less $PM_{2.5}$. See Table 6 for the comparisons.

From these calculations, it is clear that EVs are not significantly less polluting than modern ICEVs in terms of PM. We can also see that non-exhaust emissions currently account for more than 90% of PM_{10} and 85% of $PM_{2.5}$ emissions from traffic. These proportions are likely to keep increasing in the future as increasingly strict emission limits result in higher exhaust standards (EU, 2007).

Several studies have reached the same conclusion on the importance of non-exhaust emissions. Rexeis and Hausberger (2009) predicted that the percentage of non-exhaust PM of the total PM emissions will increase from 50% in 2000 up to 80–90% by 2020. Jörß and Handke (2007) modelled non-exhaust emissions of $PM_{2.5}$ in Germany and found that non-exhaust sources accounted for 25% of traffic $PM_{2.5}$ emissions in 2000 and are expected to contribute 70% of traffic $PM_{2.5}$ by 2020. This conclusion was also reached by Denier van der Gon et al. (2013), who predicted non-exhaust will likely be the dominant source of total PM emissions from traffic by 2020.

Worryingly, over the last decade, we have seen a steady increase in vehicle weight in almost all segments (International Council on Clean Transportation, 2015). See Fig. 2. This trend is expected to apply to EVs as well, as demand for longer range EVs increases. In order to achieve a longer range, EVs need larger batteries and require more structural weight to accommodate these batteries (Shiau et al., 2009).

Therefore, non-exhaust emissions from EVs and ICEVs are likely to keep increasing in the future. Strategies designed to reduce PM pollution by restricting vehicle exhaust emissions alone will no longer be very effective (Kousoulidou et al., 2008). There is a need

Table 4
Emission inventories on average tyre wear, brake wear, road wear and resuspension for passenger cars.

Reference	Emission source	PM_{10} (mg/vkm)	$PM_{2.5}$ (mg/vkm)
EEA (Ntziachristos and Boulter, 2013)	Tyres	6.4	4.5
	Brakes	7.4	2.9
	Road	7.5	4.1
US EPA (2014)	Tyres	6.1	0.9
	Brakes	18.5	2.3
Dutch PRTR (Klein et al., 2014)	Tyres	5	1
	Brakes	4.3	0.6
Dutch PRTR (Denier van der Gon et al., 2008)	Road	7	1.1
UK NAEI (Brown and Pang, 2014)	Tyres	7	5
	Brakes	7	3
	Road	8	4
	Resuspension	40	12
Average	**Tyres**	**6.1**	**2.9**
	Brakes	**9.3**	**2.2**
	Road	**7.5**	**3.1**
	Resuspension	**40**	**12**

Table 5
Comparison between expected PM_{10} emissions of EVs, gasoline and diesel ICEVs.

Vehicle technology	Exhaust	Tyre wear	Brake wear	Road wear	Resuspension	Total
EV	0 mg/vkm	7.2 mg/vkm	0 mg/vkm	8.9 mg/vkm	49.6 mg/vkm	**65.7 mg/vkm**
Gasoline ICEV	3.1 mg/vkm	6.1 mg/vkm	9.3 mg/vkm	7.5 mg/vkm	40 mg/vkm	**66.0 mg/vkm**
Diesel ICEV	2.4 mg/vkm	6.1 mg/vkm	9.3 mg/vkm	7.5 mg/vkm	40 mg/vkm	**65.3 mg/vkm**

Table 6
Comparison between expected $PM_{2.5}$ emissions of EVs, gasoline and diesel ICEVs.

Vehicle technology	Exhaust	Tyre wear	Brake wear	Road wear	Resuspension	Total
EV	0 mg/vkm	3.7 mg/vkm	0 mg/vkm	3.8 mg/vkm	14.9 mg/vkm	**22.4 mg/vkm**
Gasoline ICEV	3.0 mg/vkm	2.9 mg/vkm	2.2 mg/vkm	3.1 mg/vkm	12.0 mg/km	**23.2 mg/vkm**
Diesel ICEV	2.4 mg/vkm	2.9 mg/vkm	2.2 mg/vkm	3.1 mg/vkm	12.0 mg/vkm	**22.6 mg/vkm**

for new policies and measures that specifically target non-exhaust PM emissions (Amato et al., 2014).

5. Implications for policy

There are several options for future policy that have potential to reduce non-exhaust emissions. A good start would be to create maximum limits for non-exhaust emissions that all new vehicles (ICEVs and EVs) need to comply with. However, measurements of non-exhaust emissions so far have produced divergent results, depending on the measurement method used. So in order to introduce non-exhaust limits, a standardised measurement method would need to be introduced.

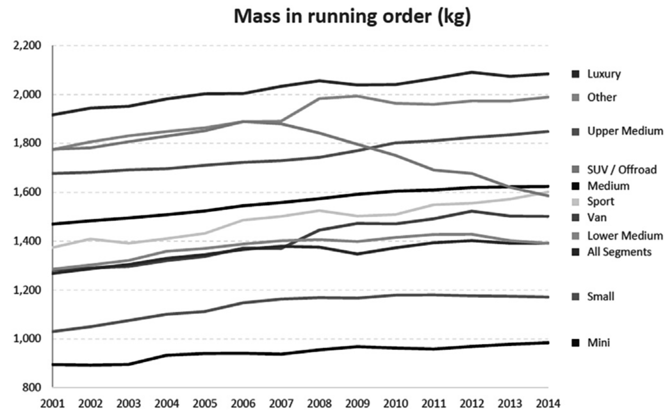

Fig. 2. Mass in running order by vehicle segment 2001–2014, adapted from (International Council on Clean Transportation, 2015).

Further improvements can be made by encouraging innovation on reducing vehicle weight. This is currently being done by the European Green vehicle Initiative (2013) to improve the range of EVs, but should also be applied to conventional passenger cars. EV technology such as lightweight body design, improved tyre design and regenerative brakes could all be applied to ICEVs to further decrease their non-exhaust emissions.

Finally, we recommend that governments create incentives for consumers and car manufacturers to switch to more lightweight passenger cars, in order to reverse the trend of increasing vehicle weight in all market segments.

6. Conclusions

Air quality in numerous places in Europe does not reach EU standards. As a result, many people experience adverse health effects due to very high concentrations of PM. Traffic is one of the major sources of ambient PM, especially in urban areas. The EV has been proposed as a solution to air pollution. Therefore, many countries are incentivising alternative fuel vehicles such as EVs.

Vehicle weight was expected to play a role in emission factors, since each of the non-exhaust emission sources is affected by weight. Several studies provided evidence that there is indeed a positive correlation between weight and non-exhaust emissions. However, more research is needed into the exact impact additional weight has on emission factors. EVs were found to be 24% heavier than equivalent non-electric models. Based on the available data, we calculated that EVs produce the same amount of PM_{10} as average conventional vehicles. EVs have slightly lower $PM_{2.5}$ emissions, emitting 1–3% less than ICEVs, on average. However, these differences are likely to disappear completely as exhaust emission standards become even stricter.

Therefore, EVs are not likely to have a large impact on PM emissions from traffic. Non-exhaust sources account for more than 90% of PM_{10} and 85% of $PM_{2.5}$ emissions from passenger cars, and this proportion is likely to increase in the future as vehicles become heavier. Policy so far has only focused on reducing PM from exhaust emissions. Therefore, future European legislation should set non-exhaust emission standards for all vehicles and introduce standardised measurement methods. In addition, it is recommended that EV technology such as lightweight car bodies and regenerative brakes be applied to ICEVs, and incentives provided for consumers and car manufacturers to switch to less heavy vehicles.

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