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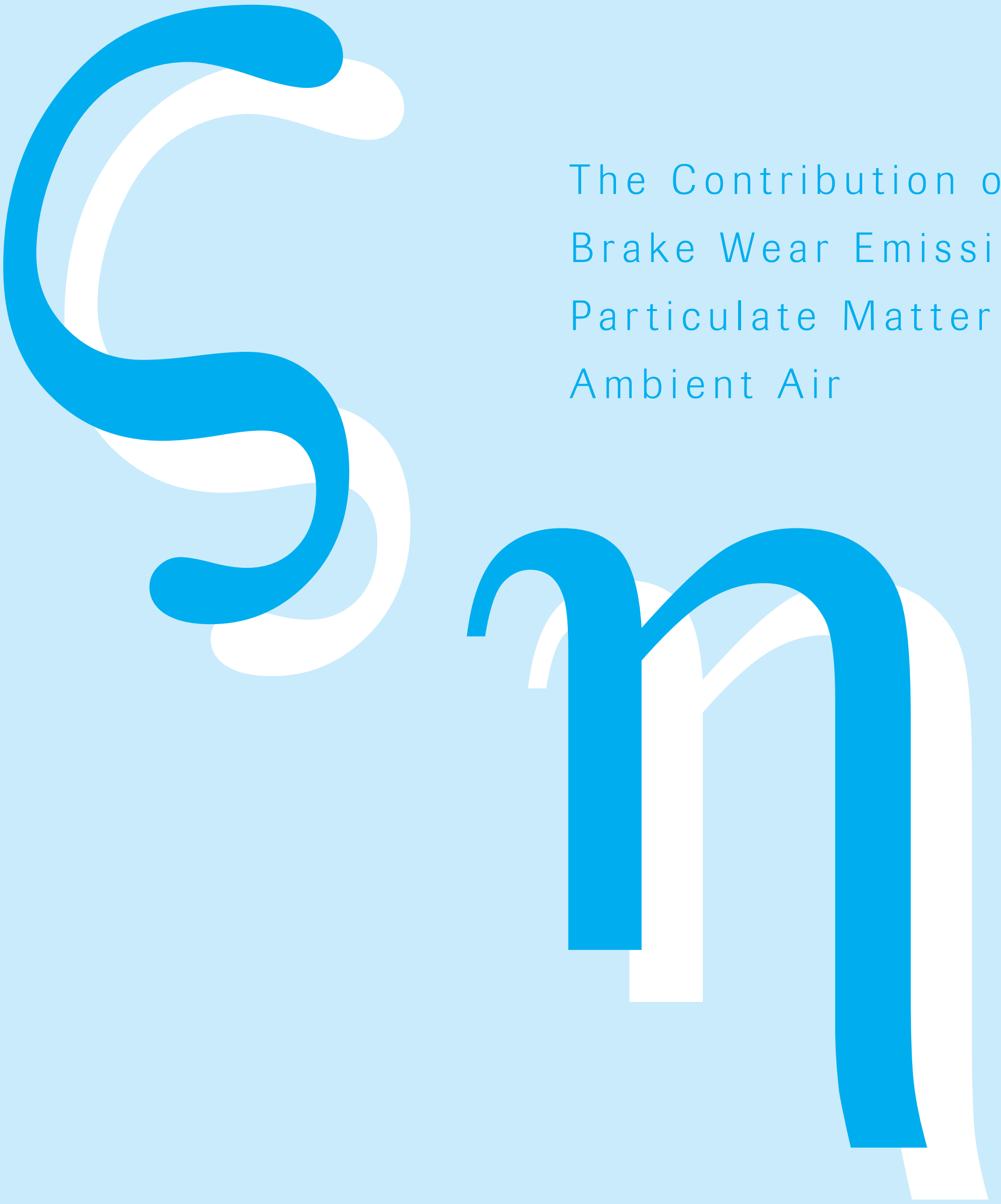
The Contribution of Brake Wear Emissions to Particulate Matter in Ambient Air



VDA
Verband der
Automobilindustrie

The Contribution of Brake Wear Emissions to Particulate Matter in Ambient Air

Forschungsstelle:
Ricardo Energy & Environment

Dan Wakeling
Tim Murrells
David Carslaw
John Norris
Luke Jones

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Executive summary/Zusammenfassung

ENGLISH

This is the final report for the project “The Contribution of Brake Wear Emissions to Particulate Matter in Ambient Air”. This report has reviewed and summarised the current evidence base for the contribution of brake wear to Particulate Matter (PM) air quality in Europe, and scoped out how uncertainties in brake wear emission estimates can be reduced, to show how such refinements could be undertaken in future assessments. To do this, the project has been split into three tasks (tasks 1, 2, and 3).

Task 1 provides a critical review of the scientific literature aimed at quantifying the contribution of brake wear, and other traffic-related sources, to concentrations of PM in ambient air. This showed that road transport contributed a considerable proportion to concentrations of PM in the air, and that this contribution is highly spatially and temporally variable. The results of this task also showed that there were few articles that explicitly provided an estimate of the contribution of the brake wear to concentrations of PM in the air. Of the studies that did provide estimates, the contribution of brake wear ranged from around 5-10% of the PM_{10} (PM with a diameter of 10 microns or less) concentrations in busy urban roadside areas (~0.8 $\mu g\ m^{-3}$ to 4 $\mu g\ m^{-3}$). At quiet rural roads, the contribution would likely be much less, and for context, the contribution of brake wear to the UK’s national inventory estimates of PM_{10} emissions for the year 2015 was 1.7%. An estimated contribution of 11% was also provided for PM_{10} measurements made in a motorway tunnel. An important finding from this section was that the literature shows that there are considerable uncertainties in estimating the contribution of brake wear to ambient PM concentrations.

Task 2 considered brake wear contributions according to national emission inventories, by analysing national inventory emissions data reported by the UK and Germany. This was useful to show how emissions from different sources (including brake wear) compare now and in the future. This showed that non-exhaust emissions are expected to increase slightly from 2015 to 2030 whilst exhaust emissions are expected to decrease dramatically. Taking the UK as an example, the inventories suggest the contribution from exhaust sources of $PM_{2.5}$ (PM with a diameter of 2.5 microns or less) will decrease from 43% of all road transport emissions in 2015 to 7% by 2030. This suggests that road transport exhaust emissions will have only a minor contribution in the future and the focus for road transport emissions abatement may well be better placed on non-exhaust emissions, if needed.

Task 3 provides a scoping study into how uncertainties in brake wear emission estimates can be reduced, and their contribution to PM air pollution can be reduced. This section describes how a ‘brake use inventory’ could be developed to provide a better estimate of where brakes are used. This section also describes the work that would be needed to inform this, including: making high temporal resolution measurements of metal tracers; and contacting industry to obtain better data on the composition of brake pads used in Europe.

A further part of task 3 lays out a modelling approach to improve the understanding of the contributions of brake wear related compounds to ambient concentrations of PM_{10} and $PM_{2.5}$ in the context of daily and annual mean concentration limits (section 4.1.2). High resolution, publicly available data from real vehicle journeys was analysed to develop a proxy for braking; negative Vehicle Specific Power (VSP). This was mapped using open source software to demonstrate the typical pattern and likely magnitude of brake use expected in real journeys, to develop a better understanding of brake use spatially. This demonstrated that the pattern of negative VSP versus exhaust nitrogen oxides (NO_x) emissions was anti-correlated, as expected. This analysis also showed that the highest intensity braking was seen at motorway exit/slip roads. It is then further described how this approach could be applied and developed to better inform emissions from brake wear and how this affects ambient PM concentrations at a high spatial resolution.

A further part of task 3 considered brake wear emissions from future vehicle technologies (section 4.2). The future and emerging technologies were considered in terms of their opportunities to reduce PM emissions. This led to a scoring system based on the likelihood of their uptake on different vehicle

types and the likelihood of their impact on reducing PM emissions. This was to highlight where reductions in brake wear emissions are likely to occur in future, on what vehicle types and over what timeframe. This could be used to prioritise where further research into brake wear emissions should be made. This scoring system indicated that inventories of PM emissions should pay particular attention to changes in brake wear emissions from light duty vehicles and buses using regenerative braking, taking account of their likely uptake into the fleet. Although this analysis does not indicate the extent by which brake wear emission factors might change from these systems, it does show that future research should focus on measurements of brake wear emissions from hybrid and electric vehicles with regenerative braking as well as more conventional technologies currently in the fleet.

GERMAN

In diesem Bericht ist die gegenwärtige Faktenlage zum Beitrag des Bremsabriebs zur Feinstaubluftqualität in Europa untersucht und zusammengefasst. Zudem wurde abgeschätzt, wie die Unsicherheit der Bremsabriebsemissionen verbessert werden kann. Es wurde gezeigt, wie diese Verbesserungen in zukünftigen Abschätzungen vorgenommen werden könnten. Das Projekt gliedert sich in drei Arbeitspakete (Arbeitspaket 1, 2, und 3).

Arbeitspaket 1 umfasst eine kritische Prüfung der wissenschaftlichen Literatur, die sich mit der Quantifizierung des Beitrags von Bremsabrieb und anderen verkehrsbezogenen Quellen zur Feinstaubkonzentration in der Umgebungsluft befasst. Die Analyse zeigte, dass der Straßenverkehr einen signifikanten Anteil zur Feinstaubkonzentration in der Luft beiträgt und dass der Beitrag räumlich und zeitlich stark variabel ist. Die Ergebnisse dieser Aufgabe zeigten zudem, dass nur wenige Fachartikel verfügbar sind, die explizit eine Abschätzung des Beitrags von Bremsabriebemissionen zum Feinstaub in der Umgebungsluft liefern. Basierend auf den Abschätzungen der Studien wurde der Beitrag von Bremsabrieb auf 5 bis 10% der PM_{10} (Feinstaub mit einem Durchmesser von 10 Mikrometer oder weniger) -Konzentration in verkehrsreichen städtischen Straßengebieten geschätzt (~0.8 $\mu g\ m^{-3}$ bis 4 $\mu g\ m^{-3}$). An weniger befahrenen, ländlichen Straßen ist es anzunehmen, dass die Konzentrationen viel geringer sind. Der Beitrag von Bremsabrieb zu den PM_{10}-Abschätzungen im britischen nationalen Emissionsinventar im Jahre 2015 war 1.7%. Für PM_{10} Messungen in einem Autobahntunnel wurde eine Abschätzung von 11% angegeben. Eine wichtige Erkenntnis aus diesem Teil der Arbeit ist, dass es in der Literatur bedeutende Unsicherheiten in Bezug auf die Abschätzung des Beitrags von Bremsabriebemissionen zum Feinstaub in der Umgebungsluft gibt.

Arbeitspaket 2 betrachtet den Beitrag von Bremsabrieb durch eine Analyse der Daten, die in den nationalen Emissionsinventaren im vereinigten Königreich und Deutschland gemeldet wurden. Dies zeigt, wie die Emissionen von verschiedenen Quellen (inklusive Bremsabrieb) sich heutzutage und in der Zukunft vergleichen. Zwischen 2015 bis 2030 wird erwartet, dass Emissionen von Nicht-Abgasquellen etwas ansteigen, während sich Abgasemissionen drastisch verringern werden. Zum Beispiel wird in den UK- Inventaren erwartet, dass der Abgasemissionsanteil an $PM_{2.5}$ (Feinstaub mit einem Durchmesser von 2.5 Mikrometer oder weniger) sich von 43% aller Straßenverkehrsemissionen in 2015 auf 7% bis 2030 verringern wird. Dies deutet darauf hin, dass zukünftig die Abgasemissionen des Straßenverkehrs nur noch einen geringen Anteil beitragen werden und der Fokus sich daher auf die Nicht-Abgasemissionen verlagern könnte.

Arbeitspaket 3 stellt eine Grundsatzuntersuchung dar, wie Unsicherheiten in der Abschätzung der Bremsabriebemissionen und deren Anteil an der Feinstaub-Luftbelastung verringert werden können. Dieser Teil beschreibt, wie ein ‚Bremsabriebinventar‘ entwickelt werden könnte, um besser räumlich abzuschätzen, an welchen Orten gebremst wird. Dieser Abschnitt beschreibt außerdem den nötigen Arbeitsaufwand, für zeitlich hochaufgelöste Spurenmetalmessungen, sowie mögliche Umfragen in der Industrie , um bessere Daten über die Zusammensetzung von Bremsbelägen in Europa zu bekommen.

Ein weiterer Teil des Arbeitspakets 3 illustriert einen Modellansatz, um das Verständnis der Anteile der Komponenten von Bremsabrieb an den Konzentrationen von PM_{10} und $PM_{2.5}$ im Zusammenhang mit täglichen und jährlichen Durchschnittskonzentrationen (Abschnitt 4.1.2) zu verbessern. Öffentlich erhältliche Daten mit hoher Auflösung von realen Fahrzeugfahrten wurden analysiert, um

Bremsvorgänge mittels negativer fahrzeugspezifischer Leistung (VSP) abzuschätzen. Zum besseren räumlichen Verständnis der Bremsnutzung wurde exemplarisch mit Opensource Software kartiert, um auch das typische Profil und das mögliche Ausmaß der zu erwartenden Bremsbenutzung in realen Fahrten zu demonstrieren. Wie erwartet, zeigte dies, dass es einen negativen Zusammenhang zwischen dem Profil des negativen VSP und den Abgas-Stickoxid-Emissionskonzentration (NO_x) gibt. Diese Analyse zeigte außerdem, dass auf Autobahnauf- und abfahrten die Bremsintensität am höchsten war. Es wird beschrieben, wie dieser Ansatz angewendet und entwickelt werden könnte, um bessere Information über die Bremsabriebemissionen zu erhalten und wie dies sich auf die Feinstaubkonzentration mit hoher räumlicher Auflösung auswirkt.

Ein weiterer Teil des Arbeitspakets 3 betrachtet Bremsabriebemissionen zukünftiger Fahrzeugtechnologien (Abschnitt 4.2). Zukünftige Technologien wurden auf ihr Minderungspotential hinsichtlich Feinstaubemissionen untersucht. Ein Punktesystem wurde erarbeitet, dass basierend auf der Einsatzwahrscheinlichkeit für verschiedene Fahrzeugtypen ihre wahrscheinliche Auswirkung auf die Reduzierung der Feinstaubemissionen betrachtet. Dies soll hervorheben, wo eine zukünftige Reduktion von Bremsabriebemissionen am wahrscheinlichsten ist und in welchen Fahrzeugtypen und in welchem Zeitraum. Dieses könnte zur Priorisierung benutzt werden, wo weitere Forschung im Bereich der Bremsabriebemissionen unternommen werden sollte. Das Punktesystem zeigte, dass sich Inventarbetrachtungen von Feinstaubemissionen besonders mit Änderungen von Bremsabriebemissionen von leichten Nutzfahrzeugen und Bussen befassen sollten, welche regeneratives Bremsen nutzen. Zwar zeigt diese Analyse nicht, in wieweit sich die Bremsabriebemissionsfaktoren dieser Systeme verändern würden. Es demonstriert jedoch, dass zukünftige Forschung sich auf die Messungen von Bremsabriebemissionsfaktoren von Hybrid- und Elektrofahrzeugen mit regenerativen Bremsen konzentrieren sollte, genauso wie auch auf herkömmliche Technologien der aktuellen Flotte.

Table of contents

1 Introduction

Fine particulate matter (PM) is present in the ambient air as a complex mixture of solid and liquid particles of organic and inorganic substances. The most health-damaging particulates are those with a diameter of 10 microns or less, (≤ PM_{10}), which can penetrate and lodge deep inside the lungs. A growing body of research has pointed towards the smaller particles, in particular PM less than 2.5 µm in diameter ($PM_{2.5}$), as a metric even more closely associated with adverse health effects. There is a close, quantitative relationship between exposure to high concentrations of small particulates (PM_{10} and $PM_{2.5}$) and increased mortality or morbidity, both daily and over time.

The EU Ambient Air Quality Directive sets a limit on ambient concentrations of PM_{10} of 50 µg m^{-3} not to be exceeded more than 35 times a year and an annual mean limit of 40 µg m^{-3}. The limit on annual mean concentrations of $PM_{2.5}$ concentrations is 25 µg m^{-3} (1). Under certain meteorological conditions, these limits can be exceeded in European cities.

A major source of PM in urban areas has been emissions from road traffic, particularly near roadsides. Exhaust emissions of PM from road vehicles have been declining in recent years. This decrease has been the result of the successful introduction of various abatement technologies driven by ever tighter vehicle emission regulations. As the importance of exhaust emissions has declined, the emissions of PM from non-exhaust sources have become relatively more prominent. These non-exhaust emissions include PM_{10} and $PM_{2.5}$ arising from the mechanical wear of brake, tyre and road surface material and traffic-induced resuspension of road dust. Emissions from these non-exhaust sources are not currently controlled.

Emission inventories provide a means of quantifying the scale of exhaust and non-exhaust emissions from road traffic and their contribution to overall emissions at national level. These emission estimates are based on vehicle activity data and average emission factors expressed in grams per kilometre (g/km). The emission factors for non-exhaust sources of PM are highly uncertain. Moreover, the concentrations of PM in the atmosphere at a given location is dependent on many other factors, including emissions from non-traffic sources, atmospheric dispersion and the formation of secondary PM in the atmosphere from other pollutants which can occur over a large regional scale. As such, apportioning the contribution of one particular source to PM concentrations in the atmosphere is non-trivial. The contribution of primary PM emissions from brake wear to urban air quality is highly uncertain.

Methods of source apportionment of non-exhaust PM have been developed based on the measurement of chemical tracers associated with brake and tyre material in sampled PM mass. In the case of brake wear, the tracers used are usually specific metals, used in brake material, and capable of being detected in ambient PM samples.

This is the draft report on a project for FAT which has aimed to review and summarise the current evidence base for the contribution of brake wear to PM air quality in Europe, and also scope out how uncertainties in brake wear emission estimates can be reduced, to show how such refinements could be undertaken in future assessments. To do this, the project has been split into three tasks.

- **Task 1 (section 2)**: a critical review of the scientific literature aimed at quantifying the contribution of brake wear, and other traffic-related sources, to concentrations of PM in ambient air. This will establish the current evidence base.

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[1] The EU Ambient Air Quality Directive also sets a National exposure reduction targets for $PM_{2.5}$ to be achieved by 2020. See Air Quality Expert Group (2012).

- **Task 2 (section 3)**: analysis of national inventory data for $PM_{2.5}$ emissions, reported by the UK and Germany in the latest year and projected to 2030. This is useful to show how emissions from different sources (including brake wear) compare now and in the future.

- **Task 3 (section 4)**: scoping study into how uncertainties in the estimations of brake wear emissions and their contribution to PM air quality on a local scale can be reduced. This task also considers brake wear emissions from future vehicle technologies and lays out a modelling approach to improve the understanding of the contributions of brake wear related compounds to ambient concentrations of PM_{10} and $PM_{2.5}$ in the context of daily and annual mean concentration limits, to show how such refinements could be undertaken in future assessments.

The conclusions of the findings of these tasks are provided in section 5, summarising the key points of this report.

2 Scientific literature review

This section of the report presents a critical review of the scientific literature aimed at quantifying the contribution of brake wear, and other traffic-related sources, to concentrations of particulate matter (PM). This is based on analysis and interpretation of current air quality measurements.

Over 30 scientific articles were reviewed, and around 2/3 of these were published after 2012. The literature search was undertaken using tools such as Google Scholar, ScienceDirect, and access to not-freely accessible sources such as the Environmental Science & Technology journal through our colleague and project team member Dr David Carslaw, who is affiliated with the University of York.

2.1 Background to brake wear emissions of PM

Based on emission inventories, which are discussed further in Section 3, road transport is a significant source of directly emitted PM. According to the UK's national atmospheric emissions inventory, road transport contributed 21% of total anthropogenic PM emissions from sources in the UK (NAEI 2014). Since emissions are concentrated on road networks in towns and cities, it is an important consideration for urban air quality policy makers.

Emissions of PM from road transport can be split into two broad categories: emissions from the exhaust tailpipe and non-exhaust emissions. Non-exhaust emission sources include tyre wear, road surface wear, corrosion, resuspensions and the focus of this study, **brake wear**. Rexeis & Hausberger (2009) estimated that by 2020, the percentage of non-exhaust PM to the total contribution of PM from road transport would increase up to 80-90%, as emissions from the exhaust tailpipe continue to fall.

Brake wear emissions are generated during periods of rapid deceleration, when brakes generate large amounts of frictional heat leading to the degradation of brake linings and discs. As a result, these non-exhaust emissions are mainly larger, coarse particulates comprised of the heavy metals that are present in brake parts such as zinc, copper, iron and lead (Thorpe & Harrison 2008). Smaller, finer particles are emitted by the volatilisation and condensation of brake pad materials (Pant & Harrison 2013). Brake wear emissions will be concentrated in areas where rapid deceleration is likely to occur, such as at junctions, traffic lights and corners.

There are two widely used brake system configurations; **disc brakes**, and **drum brakes**. Drum brakes tend to be a more enclosed system than disc brakes, which means that a greater proportion of the particles released do not get emitted to the atmosphere, instead, becoming trapped within the drum brake system. For this reason, emissions to the atmosphere from drum brakes tend to be lower than from disc brakes (Hagino et al. 2015; Hagino et al. 2016). Historically, drum brakes have tended to be more widely used in heavy duty vehicles (HDVs), relative to light duty vehicles (LDVs), although HDVs are using disc brakes more now (EMEP 2013).

Whilst exhaust emissions of PM are becoming increasingly regulated, non-exhaust sources of PM emissions, including brake wear, remain largely uncontrolled. Across the EU, road transport has been subject to the European emission standards, which have gradually reduced the permitted mass of particulate matter emissions from exhausts of diesel vehicles since their inception in the 1990s[2]. Technological advancements, such as the development of vehicle particulate filters have been effective in allowing vehicle manufacturers to achieve these progressively tighter standards.

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[2] Limits on PM mass emissions from new gasoline cars have been in place since the introduction of Euro 5 standards in 2010. Limits on particle number emissions are in place for diesel light duty vehicles from Euro 5 standards in 2010 and from gasoline vehicles with direct injection from Euro 6 standards in 2015.

One of the strategies adopted by many European countries to improve air quality and reduce greenhouse gas emissions has been to incentivise electrification of passenger cars, and as a result, removing exhaust emissions from this source (EAMA 2015). However, some studies have found that electrification of the passenger car fleet may not reduce levels of PM as much as expected, due to the relatively large weight of electric vehicles and the effect that could have on increasing non-exhaust emissions (Timmers & Achten 2016). Consequently, future policies and air quality plans may exert little additional control over overall road transport PM emissions, due to lack of regulation on PM emissions from non-exhaust sources. Until regulation is introduced, the current trend of increasing dominance of non-exhaust emissions on the overall road transport contribution to PM air quality is likely to continue.

2.2 Determining the contribution of road traffic to concentrations of PM in the air

Unlike most gaseous pollutants, PM is not a defined chemical entity and this makes it very difficult to determine the contribution of different sources to measured concentrations in ambient air. PM consists of a very wide range of chemical components that can also have a very wide range of physical properties and sizes that can vary in time and by location. Measuring concentrations of PM in ambient air is also not trivial and depends on the methods deployed. The European air quality directive defines the methods and procedures for measuring PM in ambient air, but this does not include determination of their chemical composition and does not always align with methods used to determine source emission rates. The metrics used in ambient air quality standards are defined by the measurement techniques themselves.

There are very few direct measurements of the contribution of road traffic emissions to ambient PM air quality. Methods based on the chemical components of PM measured at a few locations and their relationship with sources have been used to determine the contribution of sources to measured PM mass concentrations at certain locations. The two main methods used to quantify sources of PM are referred to as Chemical Mass Balance, where the entire mass of different components making up a measured sample of PM are accounted for, and Positive Matrix Factorisation which involves a highly complex statistical approach looking at correlations between PM components.

Figure 1 shows the results of a source apportionment study (Air Quality Expert Group 2012), showing the estimated sources of $PM_{2.5}$ in 2009 in the city of Birmingham, UK. This shows that traffic sources were estimated to contribute 16% to the ambient $PM_{2.5}$ concentrations. A breakdown between the traffic sub-sources (e.g. exhaust, brake, and tyre) was not provided. It is also worth mentioning that three of the segments are natural sources (e.g. sea salt) and secondary sources formed from chemical reactions involving other pollutants in the atmosphere: secondary organic, and secondary inorganic aerosols. Together, these make up 42% of the total. Some of these secondary sources will have arisen primarily from traffic however.

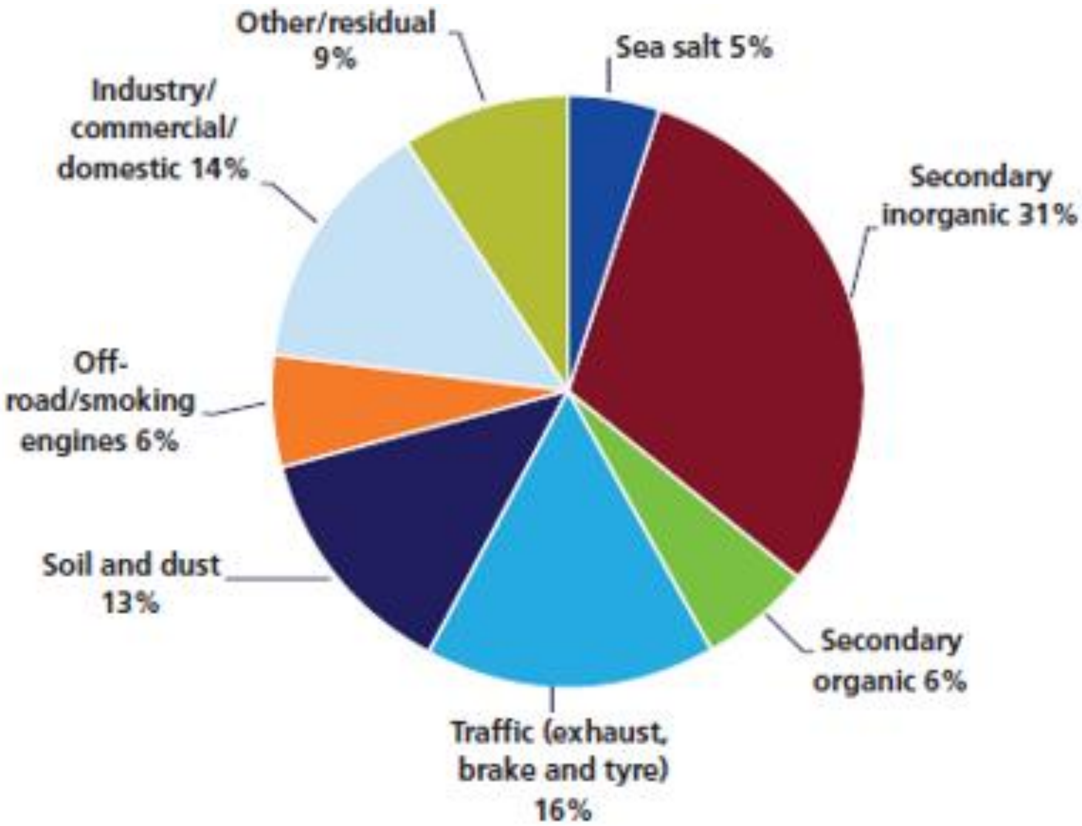

Figure 1 Results of a source apportionment study of the estimated sources of $PM_{2.5}$ in 2009 for Birmingham, UK, from the Pollution Climate Mapping model, from 2009 (Air Quality Expert Group 2012).

The source of these results did not show similar results for PM_{10} at the same site for comparison with these results for $PM_{2.5}$. Such a comparison can be made from analysis of data from a separate source of information covering different locations. This is presented in Figure 2 based on data from Karagulian et al. (2015). Karagulian et al. (2015) is a review of source apportionment studies, and the selected study from this article chosen here is a study by Carruthers et al. (2005). This study was chosen as it contains data on the contribution of traffic and both $PM_{2.5}$ and PM_{10} (Figure 2). It also provides data for a large urban site (Birmingham, UK) and a rural site (Harwell, UK), estimated for the calendar year of 2002.

Figure 2 shows that traffic sources contribute a higher proportion of the ambient $PM_{2.5}$ relative to the ambient PM_{10}, at both Birmingham and Harwell. Traffic contributed an estimated 11% of $PM_{2.5}$ at both sites. For PM_{10}, traffic contributed an estimated 7% at Birmingham and an estimated 5% at Harwell.

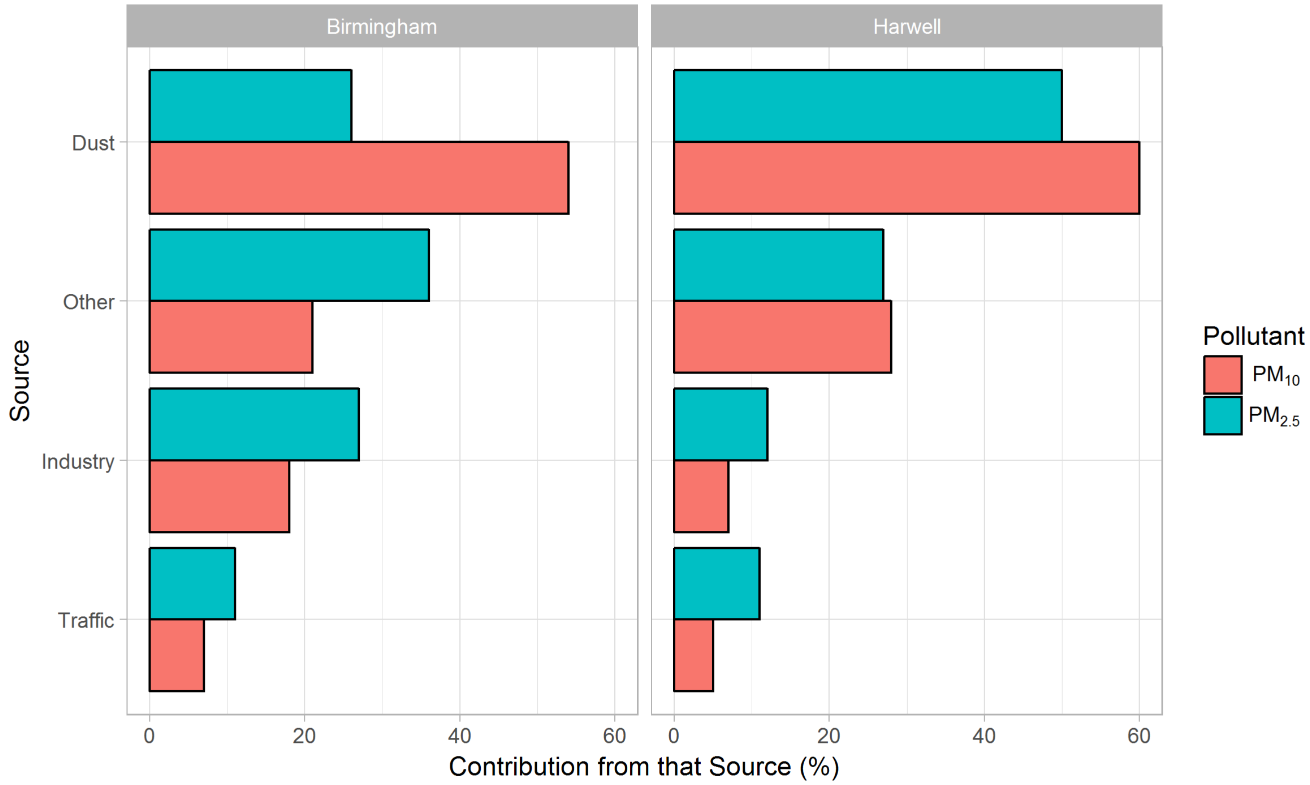

Figure 2 Source apportionment of Particulate Matter by Source for two UK sites in 2002. Data from Karagulian et al. 2015, based on Carruthers et al. 2005.

It is important to clarify that such **source apportionment studies are highly spatially and temporally variable**. This is highlighted in the differences between Figure 1 and Figure 2, as traffic is estimated to contribute 16% to $PM_{2.5}$ concentrations in Figure 1, yet only 11% in Figure 2. Hundreds of different source apportionment studies are included in Karagulian et al. (2015), and to emphasise this point further, the contribution of traffic to PM concentrations varies considerably from as low as 1% (a rural site in Poland, 2005), to 85% (Granada, Spain, 2009/2010). The estimated contributions will vary significantly depending on factors such as the site location, time measured, and the underlying model method and assumptions. For these reasons, results shown in Figure 1 and Figure 2 are not directly comparable as they are from different studies (with likely different methods and model assumptions) and for different years. There is also uncertainty in the values given, with non-exhaust sources considered to be one of the most uncertain sources to estimate (Air Quality Expert Group 2012).

2.3 Determining the contribution of brake wear to concentrations of PM in the air

Section 2.2 addressed the overall contribution of road traffic to ambient PM air quality, but not the individual contributions of brake wear and other non-exhaust sources from traffic. To do this, most studies rely on near-road measurements of particle characteristics in ambient samples such as chemical composition and particle size distributions. These ambient measurements inherently include PM from many other sources such as exhaust emissions, other non-exhaust emissions and secondary PM from distant sources, but aim to isolate the contribution from brake wear relying on the use of chemical **tracers.** These are chemical elements that exist in brake pads, for example, but are not common in other sources.

A review article from 2013 identified the key tracers used for source characterisation of non-exhaust emissions, including brake wear (Pant & Harrison 2013). This review found that copper (Cu), and antimony (Sb) are the most popular tracers used and that barium (Ba) and iron (Fe) are also commonly used. Though these are considered to be the most appropriate chemical tracers, there is significant uncertainty in applying these to estimate brake wear contributions to ambient PM. These tracers have been identified as they are commonly used in brake pad material, however the quantities of these metals used in brake pads will vary spatially and temporally (Jones et al. 2013), reflecting different manufacturers' approaches, and the scale and nature of this variation is not well understood. Also with this tracer approach it is difficult to distinguish between directly emitted and re-suspended material**.** The rest of this section summarises the available literature that have used tracers to estimate the contribution of brake wear to ambient PM concentrations.

Harrison et al. (2012) measured $PM_{0.9\text{-}11.5}$ (PM of the size range 0.9-11.5 µm) and various metal tracers in London. This study measured simultaneously at a busy urban road (Marylebone Road), and two "urban background" sites (sites that are in urban areas but sufficiently far from any busy roads) to allow them to estimate a traffic increment (the concentration difference between the urban roadside and the urban background sites). They estimated that brake dust contributed 55.3% to the traffic increment. They also provided a $PM_{0.9\text{-}11.5}$ traffic increment of 5.0 µg m^{-3}. They noted however that this traffic increment provided was likely an underestimate, as they suspected that some of the particle mass was lost due to vaporisation, a process where the particles change chemical state to become gaseous and therefore lost in the particle measurements. These values allow the calculation of a rough estimate that brake wear contributed 2.8 µg m^{-3} to ambient $PM_{0.9\text{-}11.5}$. For context, the annual mean PM_{10} concentrations at Marylebone Road in 2012[3] was 38 µg m^{-3}.

Figure 3 is taken from Harrison et al. (2012) and shows the size distribution of the particles attributed to the different non-exhaust traffic sources. The red line shows brake wear, the purple line shows tyre wear, and the green line shows resuspension. This shows that the measured PM from brake wear has a unimodal size distribution (i.e. there is only one peak of the red line along the x-axis), and that this peaks at around a size of 3 µm. This is around the cut-off point for the size considered as $PM_{2.5}$ (2.5 µm). This finding also agrees with the results of Wåhlin et al. (2006), which found that the mass median particle size was ~2.8 µm.

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[3] LondonAir. http://www.londonair.org.uk/london/asp/advstatsaqobjresults.asp?site1=BT5&site2=CT8&site3=MY1&site4=MY7&sday=1&smonth=jan&syear=2012&Submit=View [Accessed on 03/05/2017]

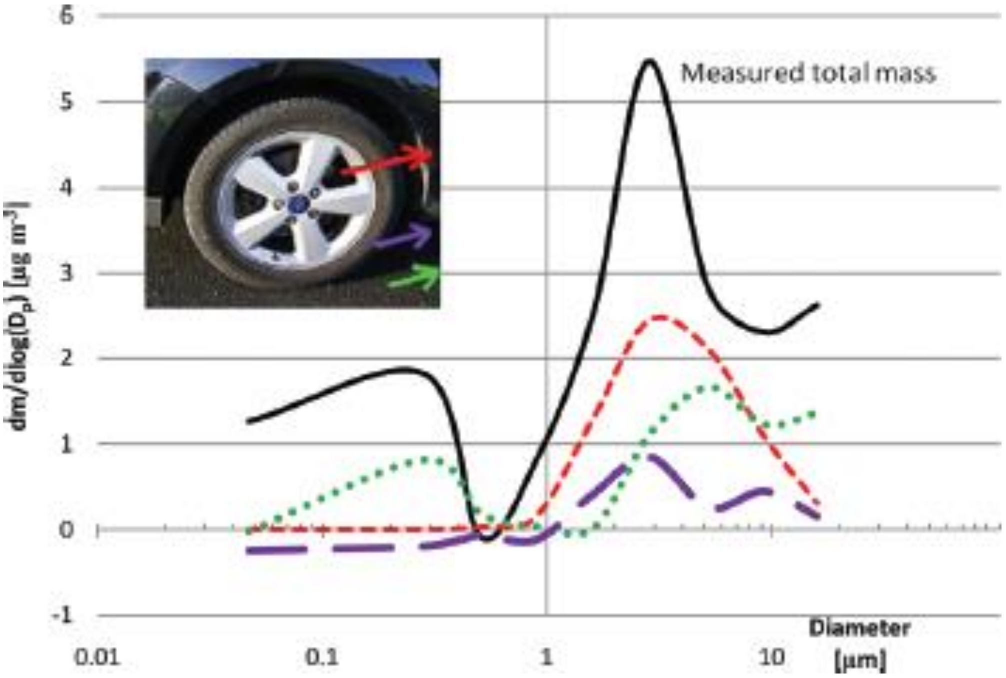

Figure 3 Size distribution of the particles measured by Harrison et al. (2012) at the Marylebone Road site in London. The red line shows brake wear, the purple line shows tyre wear, and the green line shows resuspension

Wåhlin et al. (2006) measured PM in Copenhagen, Denmark. This study found that the **contribution of brake wear to ambient PM concentrations was small but highly uncertain**. Figure 4 shows the source apportionment of roadside increments of fine fraction (~$PM_{2.5}$) and coarse fraction (~PM_{10}) from Wåhlin et al. (2006). This shows that the contribution of brakes is relatively small, instead dominated by “Road” sources (road dust due to tyre wear and resuspension) in the coarse fraction, and “Road” sources and exhaust in the fine fraction. The average estimated contribution of brake wear to the ambient PM concentrations was 0.72 µg m^{-3} ($PM_{2.5}$) and 0.80 µg m^{-3} (PM_{10}). For context, the average measured concentrations from all sources were 15.4 µg m^{-3} ($PM_{2.5}$), and 17.5 µg m^{-3} (PM_{10}) for the central urban roadside site considered. This gives estimated contributions of brakes to ambient PM concentrations of ~ 5% for both $PM_{2.5}$ and PM_{10}.

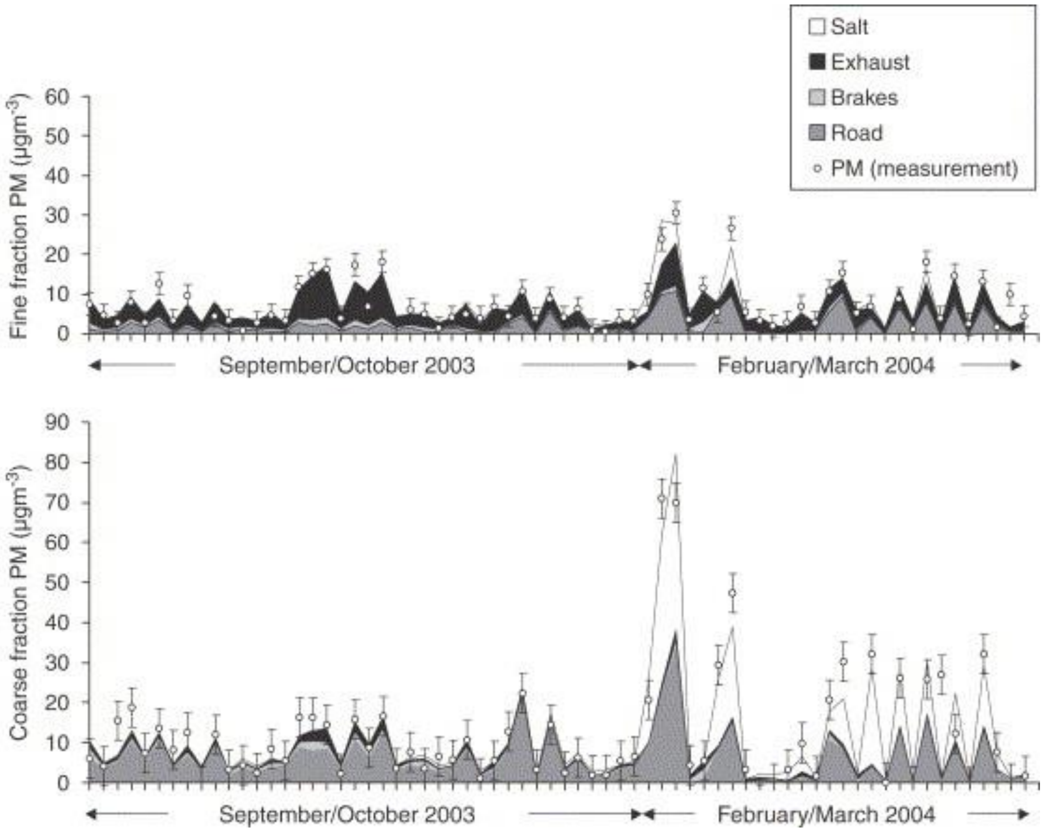

Figure 4 The apportionment of local PM (road increments) during the summer campaign (September/October 2003) and the winter campaign (February/March 2004) in Copenhagen. Fine fraction (~$PM_{2.5}$) is shown in the upper chart, coarse fraction (~PM_{10} minus $PM_{2.5}$) in the lower chart (Wåhlin et al. 2006)

Lawrence et al. (2013) measured PM_{10} in a motorway tunnel in London. This study found that brake wear contributed 11% to the PM_{10} measured. Given the nature of the site, it is unsurprising that this is larger than the percentage contribution given by Wåhlin et al. (2006) of 5%.

Contributions of brake wear to ambient PM concentrations were also estimated in a workshop report by TNO, a Dutch organisation for applied scientific research (Denier van der Gon et al. 2013). This workshop brought together European experts on road transport emissions to consider the policy relevance of wear emissions. One of the working groups estimated that the contribution of wear emissions (brake + tyre + road abrasion) at Marylebone Road, London was ~ 5 μg m^{-3} (>10% of ambient PM_{10} concentrations). Another working group estimated that the contribution of wear emissions (brake + tyre + road abrasion) near roads in Central/Western Europe was ~ 1-3 μg m^{-3}. It is important to emphasise that these values are estimated based on expert opinion.

Bukowiecki et al. (2010) quantified the non-exhaust fraction of traffic related PM_{10} for two roadside locations in Switzerland; an urban street canyon with heavily congested traffic, and an interurban motorway. They found that the contributions of brake wear to the traffic related PM_{10} were 21% and 3% respectively at the urban street canyon and interurban motorway sites. Given the likely more stop-start nature of the traffic at the urban street canyon location, the higher brake wear contributions there are unsurprising.

Two review articles stated that *"...brake wear contributions vary from negligible up to 4 μg m^{-3}"* and cited various studies to support this (Grigoratos and Martini (2015) and Amato et al. (2014)). However, reviewing the articles cited with this quote did not identify which article gave a contribution of 4 μg m^{-3}.

2.3.1 Uncertainties in estimations of brake wear contributions to ambient PM

An important message to take from this section is that there is **considerable uncertainty in the contribution of brake wear emissions** to ambient PM concentrations. Harrison et al. (2012) stated that their estimates were subject to considerable uncertainties that were not quantifiable. Denier van der Gon et al. (2013) states that "*there is a clear lack of data in the field of road transport wear (…) emissions to conclusively assess its importance for air quality and the impact on human health*" and that "*it is uncertain to what extent non-exhaust emissions contribute to ambient concentrations of* PM_{10} *or* $PM_{2.5}$".

Other sources also note this uncertainty. Pant & Harrison (2013) stated that "*quantitative knowledge of the contribution, especially of non-exhaust emissions to PM concentrations remain inadequate*" and Jones et al. (2013) stated that "*it is clear (…) that much work has been conducted upon the quantification of non-exhaust emissions from road traffic, but that current knowledge is highly fragmentary and incomplete*".

One reason why it is challenging to estimate the contribution of brake wear to ambient PM concentrations is that the composition of brake wear particles is reported to vary widely, therefore no single pollutant represents brake wear emissions in all locations. It is also difficult to measure and quantify given the nature of the source. Section 4.1 of this report considers how uncertainties in brake wear emission estimates can be reduced however.

Uncertainties also stem from the fact that a tracer thought to be unique to brake wear may also come from a related source. For example, Chellam et al. (2005) found barium (Ba) to be correlated with HDV activities but not LDVs which they attributed to the use of barium sulphate as a supplement to diesel fuel designed to reduce smoke. So considerable care is required in the use and interpretation of tracers for determining the contribution of brake wear to ambient PM measurements.

2.3.2 Spatial and temporal variability in brake wear contributions to ambient PM

Another important conclusion from this review is the spatial and temporal variability of brake wear emissions estimates and their contribution to ambient PM air quality. This is evident, for example, in the differing contributions of brake wear at the two site locations considered by Bukowiecki et al. (2010) and the differences in the contribution estimates of Harrison et al. (2012), Lawrence et al. (2013), and Wåhlin et al. (2006), This variability arises for many reasons, including:

- Emissions are related to where vehicles brake and as such are concentrated at junctions, traffic lights, corners, and steep downward slopes.
- Emissions are highly correlated with the velocity of the vehicle when it starts to brake, which is highly spatially variable.
- Brake pad composition, another important factor, also varies between countries and over time, leading to larger scale spatial and temporal variations.
- Emissions are highly dependent on vehicle use and behaviour which is highly temporally variable (e.g. higher at "rush hour" periods).

Another source of variability of brake wear sources to PM air quality in fractional terms is the contribution of other sources, both other traffic and non-traffic sources which vary in time and location.

Pant & Harrison (2013) also discuss this in their review article. They note that the profile of metal tracer concentrations is unique for each region, depending on factors such as traffic volume and fleet characteristics. Harrison et al. (2012) also give the special example of non-exhaust emissions from Scandinavia in winter, in which there is a distinct seasonal emissions pattern due to the use of studded tyres and road sanding in winter months contributing to tyre wear and road dust resuspension sources of PM.

Section 4.1 of this report details how brake wear emissions estimates could be better modelled to account for this spatial and temporal variability.

2.3.3 Summary of findings

This section has reviewed available evidence on the contribution that brake wear makes to ambient PM air quality. This evidence has been drawn from the scientific literature. A summary of the evidence gathered in section 2.3 is provided in Table 1. Table 1 shows that the estimated contribution of brake wear to ambient PM_{10} concentrations at urban roadside sites ranges from around 0.8 µg m^{-3} to 5 µg m^{-3}.

Table 1 Summarising table of the findings of section 2.3 on the contribution of brake wear to concentrations of PM in the air

Study	Estimated contribution of brake wear to ambient PM_{10} concentrations	Method/notes
Harrison et al (2012)	~ 2.8 µg m^{-3} ($PM_{0.9}$-$PM_{11.5}$ size fraction)	Based on measurements at Marylebone Road, a busy urban road in London. Estimated the roadside increment and the % of this attributable to brake wear from tracer measurements. The 2.8 µg m^{-3} is not explicit in the report, but calculated by Ricardo Energy & Environment.
Grigoratos et al (2015) and Amato et al. (2014)	negligible to 4 µg m^{-3}	Estimate from review article, though struggled to find evidence to support these values in the sources cited.
Wåhlin et al (2006)	0.8 µg m^{-3}	Based on tracer measurements in Copenhagen, Denmark. For context, the average measured concentration was 17.5 µg m^{-3} (PM_{10}).
Lawrence et al (2013)	11% of PM_{10} measured	Based on measurements in a motorway tunnel in London.
Bukowiecki et al (2010)	21% and 3% respectively of the traffic-related PM_{10} at the urban street canyon and interurban motorway sites	This article quantified the non-exhaust fraction of traffic-related PM_{10} for two roadside locations in Switzerland; an urban street canyon with heavily congested traffic, and an interurban motorway.
Denier van der Gon et al (2013)	~ 5 µg m^{-3} (>10% of ambient PM_{10} concentrations)	Working group estimate of the contribution of wear emissions (brake + tyre + road abrasion) for Marylebone Road, London.
	~ 1-3 µg m^{-3}	Working group estimate of the contribution of wear emissions (brake + tyre + road abrasion) near roads in Central/Western Europe.

During the timescale of this project it was not possible to conduct further analysis of existing air quality data, although this could be possible using advance statistical and analytical techniques which examine for correlations between PM_{10} and $PM_{2.5}$ concentrations and other air pollutants such as nitrogen oxides (NO_x) and black carbon at roadside and background sites. This may be used to separate the combustion and non-combustion components of traffic-related PM. A concept for such a method needs to be developed further.

3 Brake wear contributions according to national emission inventories

Analysis of air quality data through the tracer approach is not so useful for identifying the type of vehicles that have contributed to the measured PM from brake wear at a given location. There are no vehicle-specific tracers to measure.

Emission inventories provide an alternative means for showing the contribution of different sources to total emissions. Although emissions data from inventories alone cannot be used to understand concentrations in air because of how emissions from different sources disperse and chemically react in the air, inventories have the advantage that they can show how emissions are expected to change over time, both historically and into the future. They can also indicate the contribution of individual sources in more detail, e.g. different vehicle types. When inventories are known in enough detail, they can also be used to show how emissions are expected to vary in different locations and times. Whereas measuring PM concentrations in the ambient air and then apportioning sources is a top-down approach to understanding the contribution of brake wear emissions to PM air quality, emission inventories provide a bottom-up approach based on information on the distances that vehicles are driven, and the amount that each vehicle emits over a certain distance (i.e. vehicle-type specific emission factors).

3.1 Brake wear emission factors

Source-specific emission factors are the key information used in the development of emission factors. For brake wear, and other non-exhaust sources of PM, emission factors are expressed in grams of PM emitted per kilometre and are available for different types of vehicles.

Most studies indicate that emission factors for PM from brake wear are significantly larger from HDVs than from LDVs (Bukowiecki et al. (2010), Gietl et al. (2010), and EMEP (2013)). This would be due to the larger number or size of brakes on heavy duty vehicles and the fact that the larger vehicle weight releases more kinetic energy in the process of slowing the vehicle down. Garg et al. (2000) also found a positive relationship between the weight of vehicles considered and the associated brake wear emission factors. Table 2 shows the emission factors for tyre wear and brake wear of road vehicles as used in the UK’s National Atmospheric Emissions Inventory, submitted in 2017 (Wakeling et al. 2017). These emission factors were developed based on a method Table in the EMEP/EEA Emissions Inventory Guidebook (EMEP 2013), a Guidebook for national emissions inventory compilation. This shows, amongst other things, that the brake wear emission factors for HDVs are around 5 times higher than those from passenger cars.

The factors in Table 2 are averages for different road types and can be seen to be greater on urban roads, followed by rural roads and then motorways. This reflects the greater amount of braking done on urban roads, although this may be partially offset by the fact that the intensity of braking when it does occur would be higher on motorways where the vehicles are slowing down from greater velocities.

The relationship with speed or driving conditions and the uncertainties in these simple averaged factors are discussed in section 4.1. There are other uncertainties in the brake wear emission factors given in sources such as EMEP (2013), and other sources where emission factors have been developed from laboratory experiments (e.g. Garg et al. (2000) and Sanders et al. (2003)). The number of vehicles and tests undertaken has been very limited. These emission factors are based on small samples of vehicles and are therefore not likely to be fully representative of the fleet. The factors can be affected by artefacts in the measurements, e.g. due to resuspension of already emitted particulates, as noted in EMEP (2016) and Bukowiecki et al. (2010). Westerlund and Johansson (2002) estimated that only 20% of brake wear particles become airborne.

Table 2 Emission factors for tyre wear and brake wear for road transport vehicles as used in the UK's National Atmospheric Emissions Inventory, submitted in 2017 (Wakeling et al. 2017). These emission factors are developed based on the EMEP/EEA Emissions Inventory Guidebook 2013 (EMEP 2013).

mg PM_{10} /km		Tyre	Brake
Cars	Urban	8.7	11.7
	Rural	6.8	5.5
	Motorway	5.8	1.4
Light Goods Vehicles	Urban	13.8	18.2
	Rural	10.7	8.6
	Motorway	9.2	2.1
Rigid Heavy Goods Vehicles	Urban	20.7	51.0
	Rural	17.4	27.1
	Motorway	14.0	8.4
Artic Heavy Goods Vehicles	Urban	47.1	51.0
	Rural	38.2	27.1
	Motorway	31.5	8.4
Buses	Urban	21.2	53.6
	Rural	17.4	27.1
	Motorway	14.0	8.4
Motorcycles	Urban	3.7	5.8
	Rural	2.9	2.8
	Motorway	2.5	0.7

3.2 Analysis of national inventory data

All EU countries produce national atmospheric emissions inventories, as part of their international reporting obligations to the European Union (EU) and United Nations (UN). These emission inventories provide estimates on the emissions of PM, and other pollutants, from all known sources over the course of a year, and as such, are useful in showing how emissions from different sources compare over time, and between different countries.

On 15th March 2017, the UK submitted their latest projected emissions inventory, which estimated emissions by source for the calendar years 2015, 2020, 2025, and 2030. It is this data that is used throughout the rest of this section of the report. The UK Inventory is produced by Ricardo Energy & Environment on behalf of the UK Department for Environment, Food and Rural Affairs[4].

The Federal Environmental Agency in Germany is the compiler of the German national emissions inventory. The Agency was contacted on 17th March 2017 to obtain the data used in the projected emissions inventory for Germany. The Agency provided data from two separate inventory submissions, one submitted in 2017, and another submitted in 2015[5]. The 2017 submission was more up-to-date, however unlike the 2015 submission, it did not include projected emissions for 2020-2030 from non-exhaust sources. As the 2015 submission data are more complete for the purpose of this study, this version was used in the analysis described in this section.

It is useful to note that all national emission inventories consider only **primary, anthropogenic emissions**, as per international guidelines. These are emissions generated directly from human activities. Secondary and/or natural sources such as re-suspension of particulate matter from road dust or data on secondary pollutants formed by atmospheric transformation of primary air pollutants (such as tropospheric ozone) are not included.

3.2.1 Comparison of all source emissions

Figure 5 presents the UK's $PM_{2.5}$ emissions inventory covering all sources. Emissions from the German inventory are not readily available at this level of detail so are not presented in this sub-section.

The sources presented are:

- **Road transport – non-exhaust** (i.e. brake wear, tyre wear, road abrasion)
- **Road transport – exhaust**
- **Industry** (emissions from industrial processes)
- **Power generation**
- **Domestic combustion** (emissions arising from residential space heating)
- **Other** (any other sources that do not fit into the above source categories. These include emissions from waste processes, agricultural activities, other transport.)

Figure 5 shows that domestic combustion is the highest emissions source of $PM_{2.5}$ in all the years considered. The percentage contribution from domestic combustion varies from 42% in 2015 to 43% in 2030. The contribution from road transport – non-exhaust was 7.5% in 2015 and increases up to a maximum contribution of 9.9% in 2030. This increase indicates that the emissions strength from road transport – non-exhaust will increase relative to the other PM sources. Road transport – exhaust contributed 6 kilotonnes in 2015, which was 5.7% of the $PM_{2.5}$ emissions for that year. This percentage contribution decreases significantly by 2020, to 2.1%, and then further to 0.8% of all sources by 2030. From 2015 to 2030 the road transport exhaust emissions are estimated to decrease from 6 kilotonnes to 0.75 kilotonnes. This decline in emissions from exhausts is forecast to occur due to the continued penetration of newer vehicles into the national fleet, which have tighter PM exhaust emissions controls.

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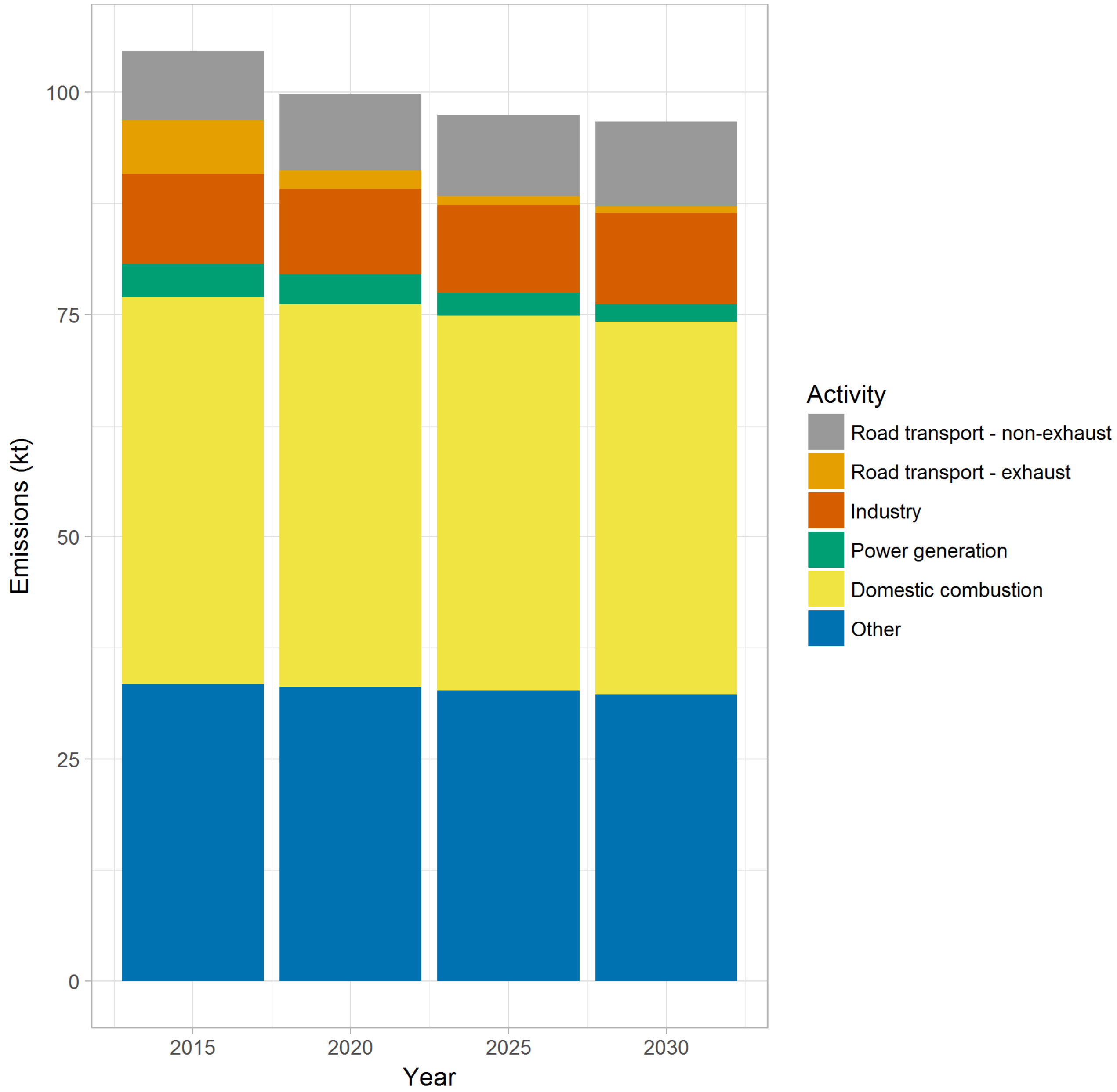
[4] UK National Atmospheric Inventory http://naei.defra.gov.uk/data/

[5] Personal communication with the Federal Environment Agency, March 2017.



Source: Ricardo Energy & Environment

Figure 5 UK emissions of $PM_{2.5}$ by source

3.3 Comparison of emissions from road transport sources

3.3.1 $PM_{2.5}$ emissions

Figure 6 presents $PM_{2.5}$ emissions for road transport sources only, from the UK and German Inventories. This shows that for both the UK and Germany, exhaust emissions are estimated to decrease rapidly from 2015 to 2030 and non-exhaust road transport emissions are estimated to increase steadily over the same period. The reduction in exhaust emissions is forecast to occur primarily due to the continued penetration of newer vehicles into the national fleet, which have tighter PM emissions controls, such as particulate filters. The steady increase in non-exhaust emissions is a reflection of an estimated steady increase in the number of vehicles driven, particularly on urban roads.

From 2015 to 2030, exhaust emissions in Germany are not predicted to fall as rapidly as for the UK. In Germany, exhaust emissions are estimated to fall to 2.2 kilotonnes in 2030, 26% of the 2015 German exhaust emissions value. In the UK however, exhaust emissions are estimated to fall to 0.75 kilotonnes, 12% of the 2015 UK exhaust emissions value. Likely reasons for this include:

- **Differences in traffic mix in each country** in terms of the activities by different vehicle types (passenger cars, light commercial vehicles and heavy duty vehicles) on different road types

- **Differences in the fleet structure** in terms of vehicle age, fuel type and Euro standard mix and turnover in the future vehicle fleet. In particular, the UK is predicting a decrease in future sales of new diesel cars in favour of gasoline cars. Historically, the UK has had a smaller share of diesel cars than Germany, but has seen a rapid growth in the new diesel car share in the last decade. This is now slowing down and the trend of increasing diesel car sales is expected to reverse.

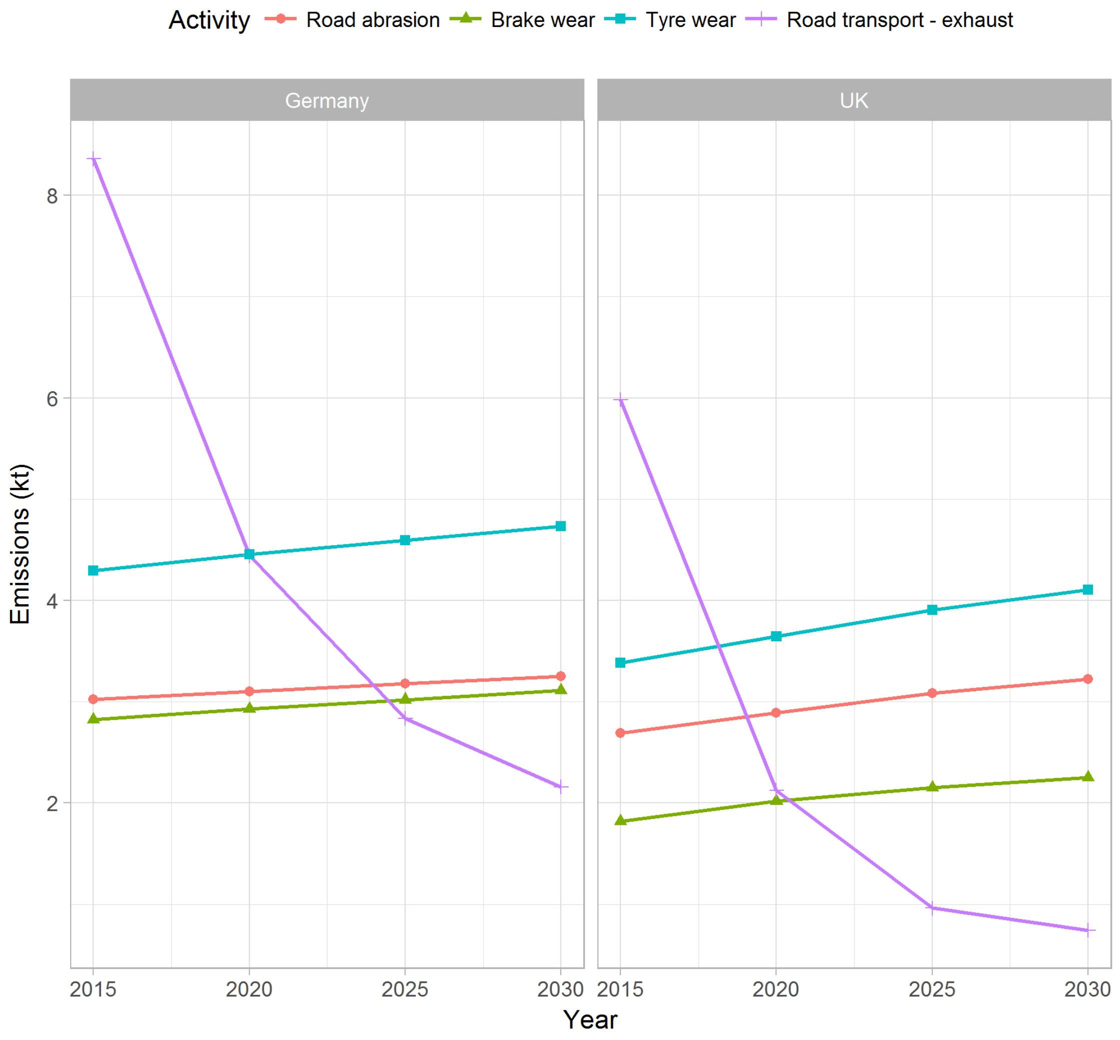
- **Differences in the methodology for estimation of exhaust emissions**. The German Inventory uses a method based on the “Handbook of emission factors for road transport“ (HBEFA) model, while the UK uses a model based on the “Computer programme to calculate emissions from road transport” (COPERT) methodology.

Emissions from non-exhaust sources increase at similar rates in both countries, probably reflecting use of the same source of emission factors and similar rates in future traffic growth estimates.

In 2015, exhaust and (combined) non-exhaust sources make a similar contribution to $PM_{2.5}$ emissions in both countries. The inventories for both countries show how the non-exhaust sources will become the dominant sources of $PM_{2.5}$ emissions from road transport by 2020 assuming no abatement measures are put into place. Taking the UK as an example, the inventories suggest the contribution from exhaust sources of $PM_{2.5}$ will decrease from 43% of all road transport emissions in 2015 to 7% by 2030. This illustrates how the lack of any abatement on emissions from these sources will significantly restrict further progress in reducing overall emissions from road transport.

Emissions from brake wear, tyre wear and road abrasion are all expected to increase at similar rates in line with traffic growth in both countries. Thus, in the UK, the overall contribution of brake wear to total road transport emissions increases from 13% in 2015 to 22% in 2030.

Figure 6 shows that the $PM_{2.5}$ emissions from road transport are greater in Germany relative to the UK. This is largely because there is more vehicle activity done in Germany relative to the UK. Figure 6 also shows that the proportional contribution from brake wear to road transport $PM_{2.5}$ emissions is greater in Germany than for the UK. This is likely due to two reasons. Firstly, the inventory data for both countries suggests that there is a higher proportion of Heavy Duty Vehicles and Buses in Germany relative to the UK. In 2013, based on the 2015 submission of the German Inventory, the proportion of Heavy Duty Vehicles and Buses in the fleet was 8% (Umweltbundesamt 2015a). In the UK, based on the 2017 submission of the UK Inventory, the proportion of Heavy Duty Vehicles and Buses in the fleet was 6%[6]. The brake wear emission factors for Heavy Duty Vehicles and Buses are much larger than for other vehicle types, so per kilometre driven, these vehicles produce more emission from braking relative to other vehicle types. Secondly, the emission factors used for brake wear from Heavy Duty Vehicles and Buses are larger in the German inventory relative to the UK inventory. In Germany, a simpler approach is used, based on emission factors from a literature study in 2006 (Umweltbundesamt 2015b). The $PM_{2.5}$ brake wear emission factor used is 12.7 mg/km for Heavy Duty Vehicles and Buses. In the UK, a more complex approach is used, based on the EMEP Emissions Inventory Guidebook (EMEP 2013). This generates a fleet-weighted $PM_{2.5}$ brake wear emission factor for Heavy Duty Vehicles and Buses of 9.9 mg/km used in the UK.



Source: German data: German Environment Agency
UK data: Ricardo Energy & Environment

Figure 6 **$PM_{2.5}$ emissions from road transport sources according to the UK and German Inventories. The scale on the y-axis applies to both countries.**

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[6] UK National Atmospheric Inventory http://naei.defra.gov.uk/data/

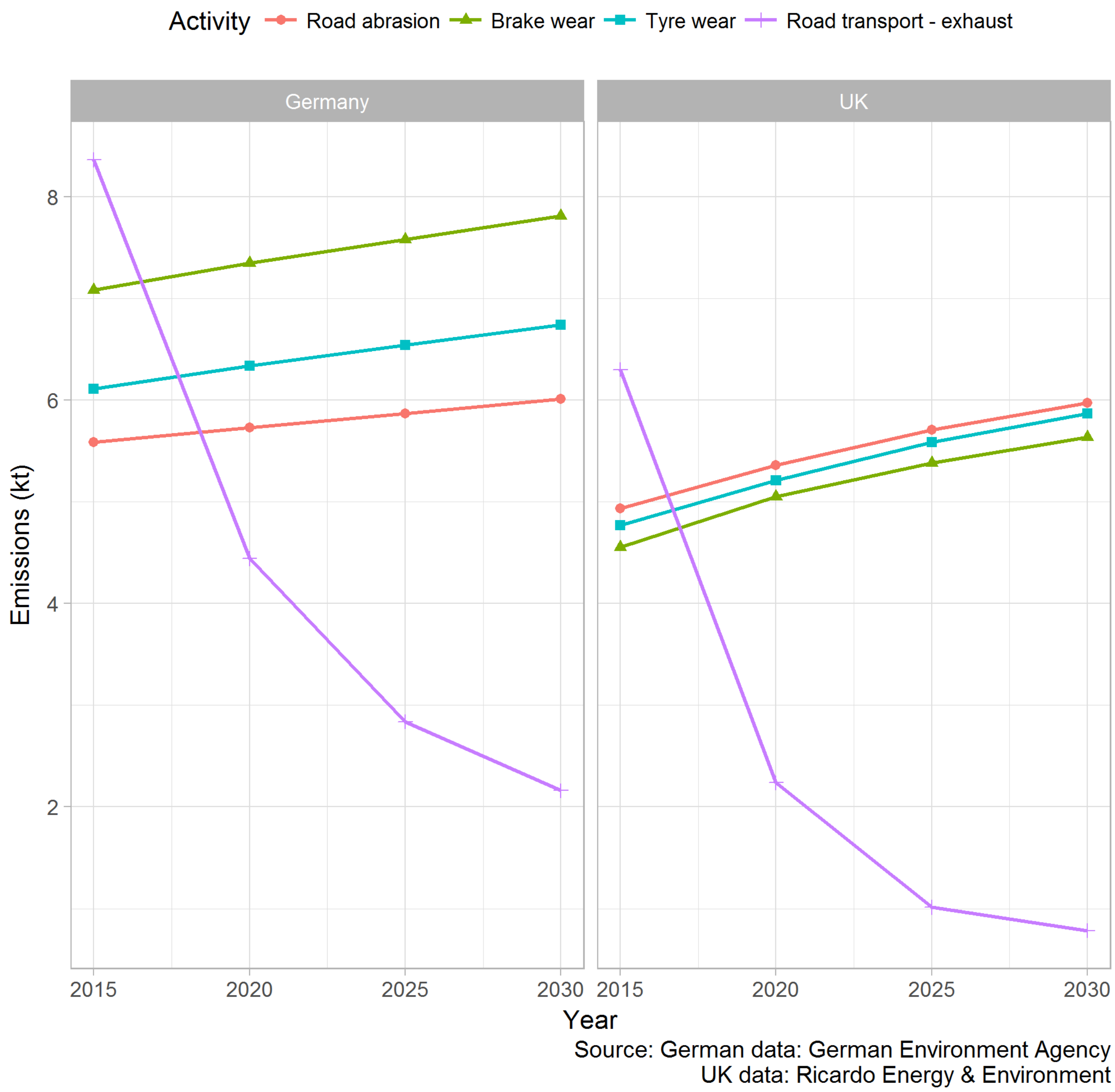
3.3.2 PM_{10} emissions

Figure 7 presents PM_{10} emissions for road transport sources only, from the UK and German Inventories. The trends are similar to those shown for $PM_{2.5}$ in that for both the UK and Germany, exhaust emissions are estimated to decrease rapidly from 2015 to 2030 and non-exhaust road transport emissions are estimated to increase steadily over the same period.

The main difference in the inventories for PM_{10} compared with $PM_{2.5}$ is the greater importance of the non-exhaust sources. The exhaust emissions of PM_{10} and $PM_{2.5}$ are very similar, reflecting the fact that the majority of the PM mass emissions from vehicle exhausts are in the $PM_{2.5}$ range. With the non-exhaust sources, this is not the case, with a greater proportion in the coarse range leading to a situation where the contribution of the non-exhaust sources to PM_{10} emissions is even higher than for the $PM_{2.5}$ emissions.

One of the main differences in the PM_{10} inventories for the UK and Germany is in terms of the relative contribution made by brake wear compared with other non-exhaust sources. For $PM_{2.5}$, the contributions were similar in both countries, whereas for PM_{10}, brake wear is the largest source of non-exhaust emissions. In Germany, brake wear becomes the dominant source of all road transport PM_{10} emissions by 2020, whereas in the UK it is the smallest source. However, the rates of increase in non-exhaust sources are similar to each other in both countries.

The reason for this difference in relative contributions of brake wear to PM_{10} emissions in the UK and Germany is not clear without further investigation. It may reflect differences in the $PM_{2.5}$ and PM_{10} size fractions used for brake wear in the inventories for each country. For example, Germany may be assuming a greater fraction of the PM emissions occur in the 10 micron range than is assumed in the UK, whereas the fractions assumed in the 2.5 micron range could be similar. Alternatively, Germany could be assuming that the brake wear fractions in the 10 micron range are similar to the UK, but decreases significantly to the 2.5 micron range. Either case implies a more significant drop in the fraction in the 10 to 2.5 micron range apparent in the German inventory compared with the UK inventory.



Source: German data: German Environment Agency
UK data: Ricardo Energy & Environment

Figure 7 PM_{10} emissions from road transport sources according to the UK and German Inventories. The scale on the y-axis applies to both countries.

3.4 Comparison of brake wear emissions by vehicle and road type

Figure 8 presents the $PM_{2.5}$ emissions from brake wear in the UK split by vehicle type and road type. Emissions from the German inventory were not readily available at this level of detail in the timescale of this project. The emissions at this level of detail are derived by combining the vehicle and road type-specific emission factors (Table 2) with vehicle kilometre data available for different vehicle and road types, as provided for the UK inventory by the UK Department for Transport (DfT). These data come from DfT’s traffic census and traffic forecasts available at this level of detail. Note that the points of the lines are offset slightly to avoid overlapping (e.g. as occurs for Heavy Duty Vehicles and Passenger cars on Motorways).

It is clearly apparent from this figure how emissions from brake wear are more dominant on urban roads than on motorways and how emissions from passenger cars dominate over other vehicle types on urban roads. The dominance of passenger cars is less on rural roads and on motorways, passenger cars and heavy duty vehicles make a similar small contribution.

Source: Ricardo Energy & Environment

Figure 8 $PM_{2.5}$ emissions from brake wear in the UK split by vehicle type (coloured legend lines) and road type (the three facet grids running from left to right).

4 Scoping study into reducing uncertainties in estimating brake wear emission and their contribution to PM air quality

4.1 How uncertainties in brake wear emission estimates can be reduced

The emission factors for brake wear have considerable uncertainty, as discussed in previous sections. The uncertainty arises for several reasons. First, the PM from brake wear does not consist of a single identifiable compound in contrast to emissions of gaseous species such as NO_x. Secondly, it is very difficult to measure and quantify brake wear emission directly given the nature of the source. Finally, there is uncertainty in the actual composition of brake pads themselves. Most attempts at quantifying emissions and their contribution to PM air quality rely on ambient measurements of metal tracers close to roads. This section considers how estimating PM emissions from brake wear in national inventories could be improved, but also how the spatial distribution of these emissions could be better represented.

In emission inventories brake wear emissions tend to be distributed spatially on the road network according to the flow and type (e.g. light / heavy) of vehicle, as derived from real traffic census data or transport models. It is difficult to know how representative and accurate is this method of representing the emissions as it does not take account of where braking activities actually occur. For example, is it the case on motorways that high flows of heavy vehicles are indicative of high brake wear emissions, albeit a lower brake wear emission factor is allocated to this type of road in the inventory calculations? Similarly, it is difficult to know whether brake wear emissions are more important in urban areas compared with non-urban areas. These issues matter because the location and potential for human exposure will vary considerably depending on where (and when) the emissions are released.

In principle, given a knowledge of vehicle types and their activity (e.g. from a traffic model) it would be possible to provide a better estimate of where brakes are used, in other words through a ‘brake use inventory’. Such an inventory would likely better apportion the PM from brake wear spatially. In principle, it would be possible from a knowledge of vehicle mass and operating conditions (vehicle speed, acceleration and slope of the road) to estimate the changes in power demand of a vehicle along a length of road. For braking, such an approach would identify the conditions under which brakes are applied together with an estimate of the energy loss in doing so. For example, it would be expected that a heavy vehicle decreasing from a high speed to a low speed would be associated with much higher brake wear emissions than a lighter vehicle decelerating at a lower speed.

The development of a brake use inventory would also have a direct relevance to the optimum location for making ambient measurements aimed at quantifying brake wear emissions of PM. Currently, the ambient studies to date have tended to use existing ambient air quality sites in urban areas. These locations, while useful indicators of air quality in relation to traffic emissions in general, may not be ideal locations for measuring brake wear emissions. The development of a brake use inventory could help identify locations where brake wear emissions would tend to be highest. For example, it might be the case that a site located close to a major junction on a road with high vehicle flows and strong decelerations would be far better.

The following section outlines a demonstration of how such a ‘brake use inventory’ concept could work.

There is currently a lack of brake composition data available, which is clearly a limitation when attempting to quantify brake wear emissions. In principle, it should be possible to identify from sales figures the most common brake pads in use in Europe. With a sample of these brake pads, the composition, e.g. of metals, could be better quantified. Such information would directly benefit the analysis of ambient data used to quantify brake wear PM. The common methods for identifying and quantifying sources from ambient measurements (i.e. the Chemical Mass Balance and Positive Matrix Factorization methods mentioned earlier) would both benefit from improved source information regarding brake wear emissions. Such information can be used either directly (CMB) or be used to constrain the statistical models used (PMF).

There are also improvements that could be made to measuring metal tracers in the ambient atmosphere. Most work to date has relied on the analysis of daily gravimetric filters to identify metal concentrations. These measurements have clearly been useful but do not provide much temporal emissions information. There are, however, instruments available that can measure *hourly* concentrations of metals based on X-ray fluorescence (XRF). An hourly time series of metal concentrations from a location where brake wear emissions are thought to be important could be highly valuable. The use of such a technique could then provide time of day and day of week concentrations for a range of important tracers such as copper. Together with a knowledge of vehicle flows (and vehicle type), there would be a much-improved opportunity to link the measurement of tracers with vehicle type and traffic volume. This type of information could help improve emission factors and emission inventory development related to brake wear emissions, as the enhanced temporal resolution XRF measurements would enable statistical analysis to improve the quantification of emission factors. Furthermore, this would allow a comparison with hourly traffic flows to help better apportion PM concentrations to vehicles. Overall, this would result in considerable reductions in emission estimate uncertainties.

4.1.1 Availability of tracer information

Air quality measurements are routinely made within Europe and maintained in a central data repository by the European Environment Agency. This is done to satisfy air quality directives, and Ricardo Energy & Environment manage the United Kingdom’s reporting for central government. This central data repository is particularly difficult to analyse on a large scale, so Ricardo Energy & Environment have transformed the observational data and inserted them into a single database of millions of observations for our use. Because of this work, this data was fit for analysis, to see what data is available on brake wear tracers.

As part of this project, the database of air quality measurements was searched for data on the most common brake wear tracers (copper, antimony, barium, and iron). Upon review, there was only data reported for copper and iron, so no data for barium and antimony. For copper and iron, there was measurements data reported from three different sites in central Europe. The highest resolution data was daily means, meaning there was no data available at the higher resolution hourly period.

This dataset covers reported measurements data to satisfy air quality directives, however this does not include all air quality measurements taken, as many are taken for example as part of field campaigns to support academic journals.

4.1.2 Development and visualisation of a modelling approach

It has been discussed above that there are significant uncertainties in the estimates of the contribution of brake wear to ambient PM concentrations, and how uncertainties can be reduced. This section will lay out a modelling approach, with the goal to improve the understanding of the contributions of brake wear related compounds to ambient concentrations of PM_{10} and $PM_{2.5}$ in the context of daily and annual mean concentration limits.

The distribution of brake wear emissions along road links is likely to be very different to that for exhaust emissions. In fact, it might be expected that these two emission characteristics are anti-correlated. To our knowledge, there are no examples of brake wear use inventories available from which in principle brake wear emissions could be estimated. However, given enough information concerning the operation of vehicles, it should in principle be possible to develop a better understanding of brake use spatially.

As an example of a potential approach, comprehensive data have been analysed from on-road Portable Emissions Measurement System (PEMS) measurements as part of UK Department for Transport research in 2016 (The UK Department for Transport 2016), and is presented in section 4.1.2.1. This data was not produced for this FAT project, but was available to Ricardo Energy & Environment for analysis. Further details are available here: https://www.gov.uk/government/publications/vehicle-emissions-testing-programme-conclusions.

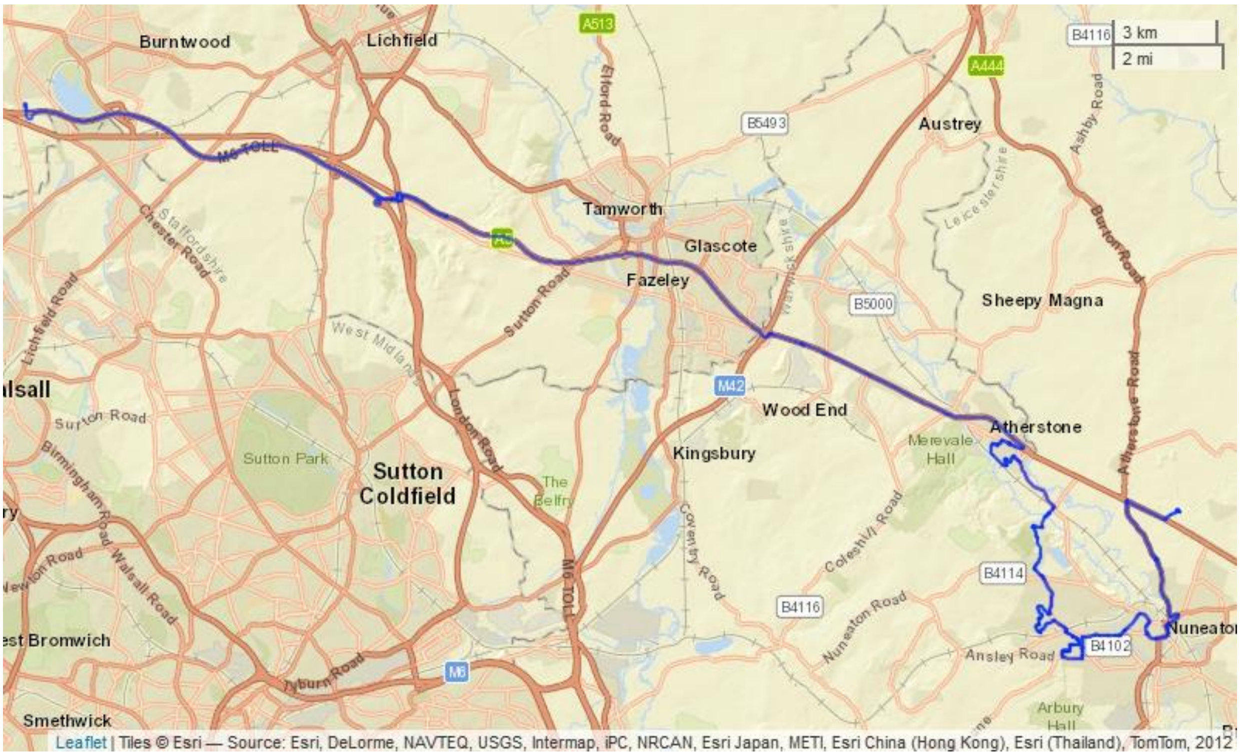
4.1.2.1 PEMS data analysis

This section presents the visualisation and mapping of the UK Department for Transport research PEMS data. This analysis includes high resolution data on the location, speed, altitude (from GPS devices attached to the vehicles) and emissions (of certain pollutants), amongst other metrics, from the PEMS. Figure 9 shows a PEMS fitted in the rear of a vehicle, as used in The UK Department for Transport (2016). 19 vehicles were tested along urban, rural, and motorway roads during the day, and under “normal” traffic conditions in central England. Figure 10 and Figure 11 show the route the vehicles took along the test route. The time it took the vehicles to cover the test route was approximately 1.5 hours. The vehicles tested were all Euro 5 or Euro 6 diesel passenger cars. Further details of the testing conditions are provided in The UK Department for Transport (2016).

Figure 9 PEMS within a test vehicle, as used in The UK Department for Transport (2016) (Figure 4-1, The UK Department for Transport (2016))

Leaflet | Tiles © Esri — Source: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2012

Figure 10 Map showing the route, indicated by the blue line, undertaken by the vehicles along the test route.



Leaflet | Tiles © Esri — Source: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2012

Figure 11 Map showing the route, indicated by the blue line, undertaken by the vehicles along the test route. Shown at a greater zoom level relative to Figure 10.

The DfT data has been processed to provide an estimate of the second by second Vehicle Specific Power (VSP). VSP is a mathematical representation of engine load required to overcome aerodynamic drag, acceleration, rolling resistance, plus the kinetic and potential energies of the vehicle, all divided by the mass of the vehicle (Jiménez et al. 1999). VSP is commonly used in vehicle emission remote sensing experiments to estimate the instantaneous power demand of a vehicle (Carslaw et al. 2013). In practice, a generic set of coefficients values estimating VSP for typical light duty vehicles is often used based on the instantaneous vehicle speed, vehicle accelaration, vehicle mass and slope. Negative values of VSP would tend to be associated with decelerating vehicles.

It is not known when brakes were actually applied in the DfT data but for illustration, it has been assumed that VSP values lower than -5 kW/tonne (kW/t) would tend to indicate braking rather than deceleration without brakes being applied. The purpose is to demonstrate the typical pattern and likely magnitude of brake use expected in real journeys. In principle, with some refinement, it should be possible to model brake use based on vehicle speed trajectories. Moreover, with increasing amounts of vehicle tracking data available, the extension of this approach to whole urban areas and even national inventories would be achievable.

It should be noted that the results shown in this section are illustrative and that it will likely be better to use a metric based on vehicle power only i.e. not mass-specific power. Such an approach would allow the mass of a vehicle to be considered directly in the calculations and lead (for example) to heavier vehicles being associated with more energy loss when decelerating – and hence higher brake emissions – than lighter vehicles.

In the rest of this section, selected interesting locations from the results of the mapping are presented and discussed.

4.1.2.1.1 Motorway exit

4.1.2.1.1.1 Vehicle Specific Power

Figure 12 shows the VSP data at a motorway slip/exit road. The VSP values are shown by the coloured circles. The lower VSP values, that are a proxy for the most intense braking, are shown by the larger, redder circes. The higher VSP values are shown by the smaller, yellower circles. Only data points where the VSP is below -5 kW/t have been shown because it has been assumed that if the VSP is above -5 kW/t then the vehicle is likely not braking. The motorway is shown by the two thick black lines running from left to right across the center of the image.

Figure 12 is annotated by two text boxes. Text box 1 highlights an area of intense braking as vehicles slow down from a high speed to take a sharp left turn to leave the motorway. High braking emissions at motorway exit sites was also observed by Abu-Allaban et al (2003). There is also a line of smaller, lighter yellow circles trailing this point, to the right of this image. This shows vehicles that started braking to take the left turn early, and so the braking is less intense.

Text box 2 highlights another area of intense braking. There is a rounadbout at the top of this area of circles that leads to a service station. The intense braking in this area will be as vehicles slow down from high speeds to approach the roundabout. On this road, the vehicles are also travelling downhill, as shown in Figure 13.

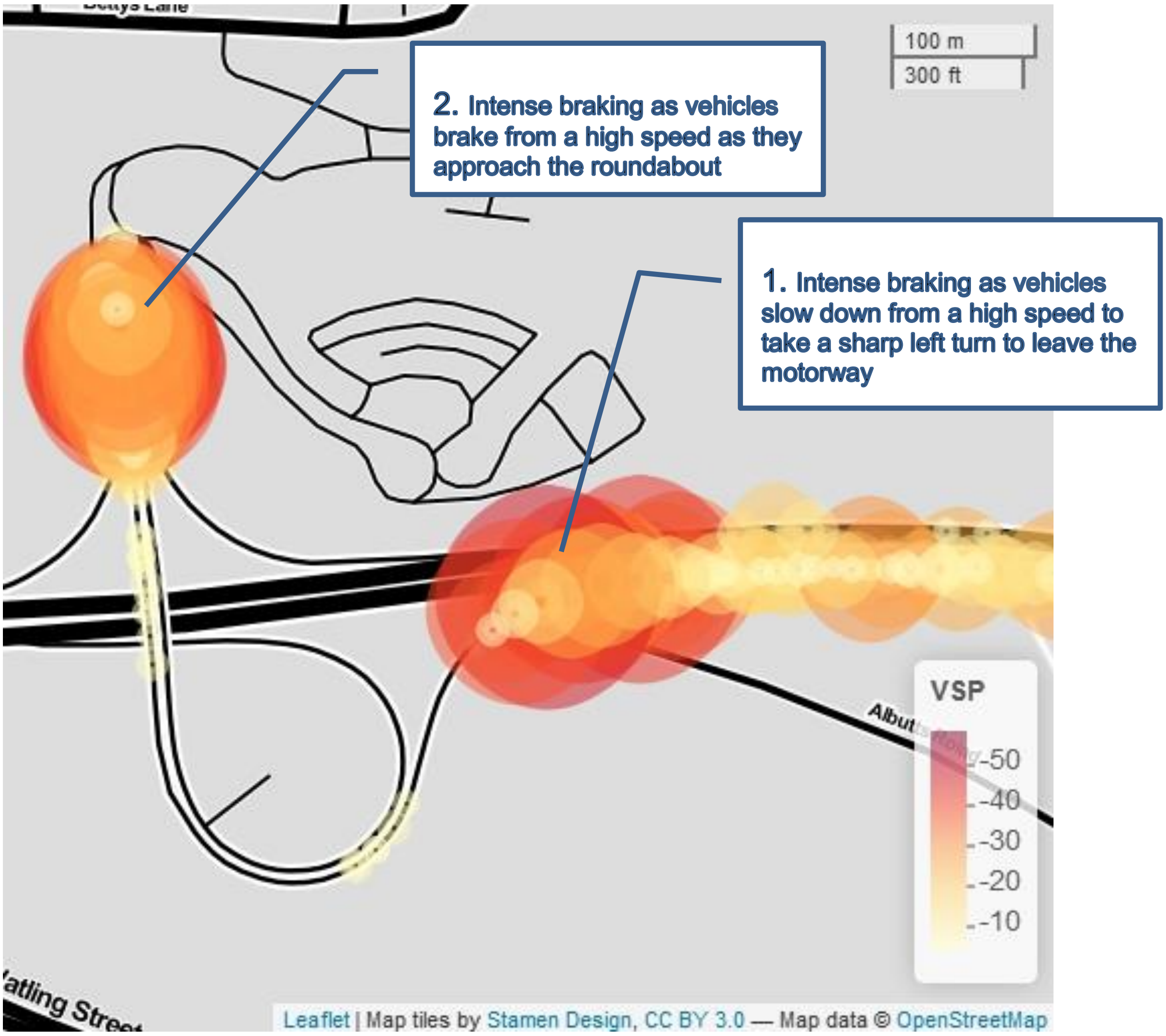


Figure 12 Visualisation of VSP (where VSP is < -5 kW/t) at a motorway slip/exit road

Figure 13 The approach to the roundabout as annotated by Text box 2 in Figure 12 (Google Maps [Accessed May 23 2017]).

4.1.2.1.1.2 Nitrogen oxides (NO_x)

As discussed above, it might be expected that the emission characteristics of braking and vehicle exhaust emissions might be anti-correlated. Figure 12 shows the negative VSP values as a proxy for brake wear emissions, however it is also useful to show nitrogen oxides (NO_x) emissions in comparsion. Whereas brake wear emissions are expected to occur where there is deceleration, the highest NO_x emissions are expected to occur where the vehicle is under the highest load (i.e areas of highest accelaration). Figure 14 shows the measured NO_x emissions in grams per second over the same area shown in Figure 12, for comparison. The data used in Figure 14 has not been filtered based on the VSP value, unlike Figure 12 however.

As expected, the pattern is anti-correlated with the results of Figure 12 i.e. regions of high NO_x are oppostite to regions of high brake use. Text box 1 shows high NO_x emissions as the vehicles re-enter the motorway from the slip road. Text box 2 also shows high NO_x emissions as the vehicles start to re-enter the motorway along the slip road. Text box 3 shows moderate NO_x emissions, where there were no VSP values below -5 kW/t, as the vehicles pick up speed after a sharp turn on the slip road.

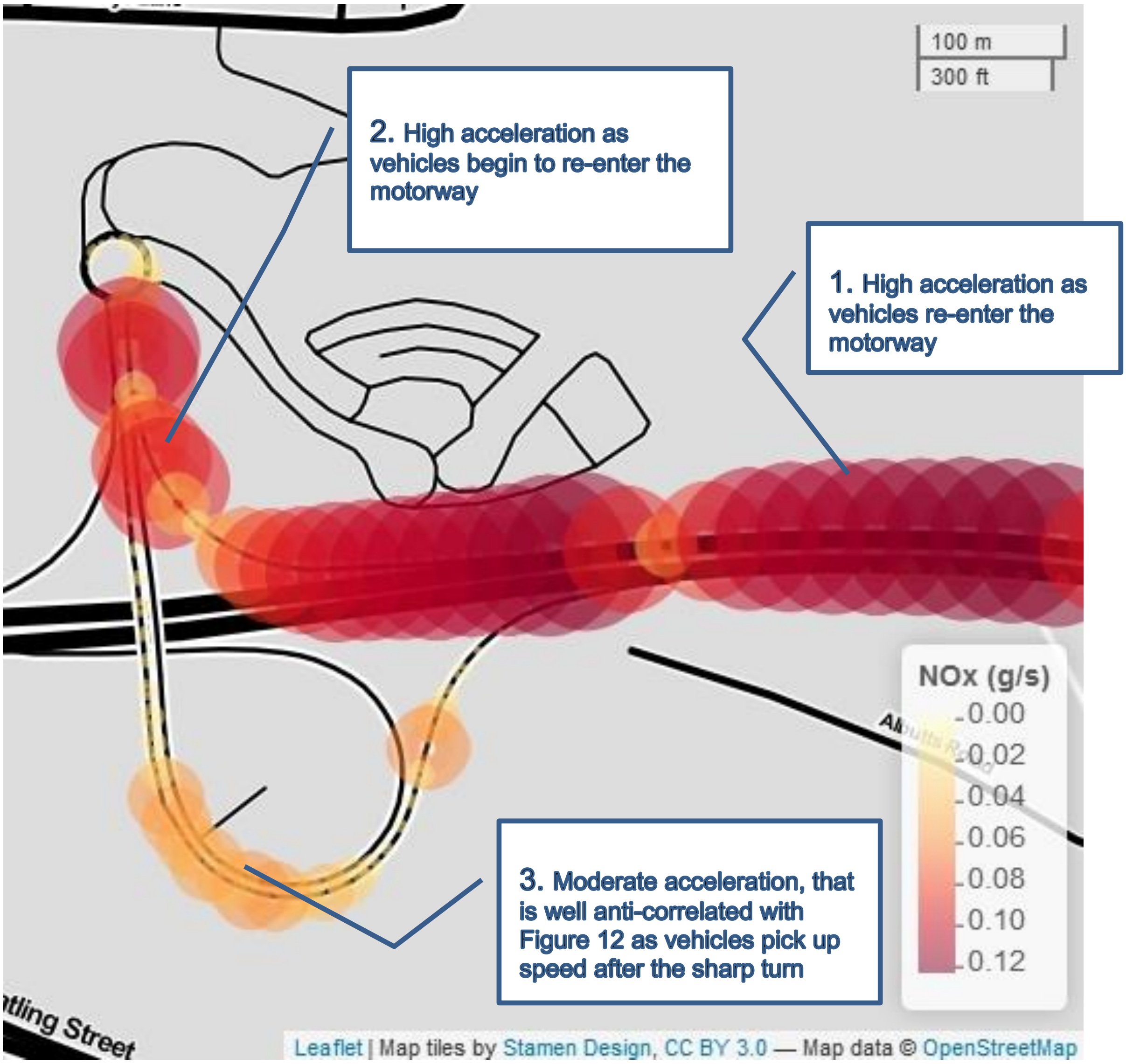


Figure 14 NO_x emissions (grams/second) at a motorway slip/exit road

4.1.2.2 Urban town

Figure 15 shows the VSP data within the urban town of Nuneaton. Nuneaton is a town with a population of around 80,000 people. As indicated by the scale in the top right of the Figure, this is shown at a more zoomed out scale to give a wider view of the VSP within the urban area. When compared against Figure 12, it is clear that across the urban area, the negative VSP does not reach the same intensity. This characteristic would suggest that higher brake wear emissions would be expected on higher speed (non-urban) roads where there is more energy loss associated from braking from high speeds. A more detailed analysis would reveal the conditions under which braking is most important.

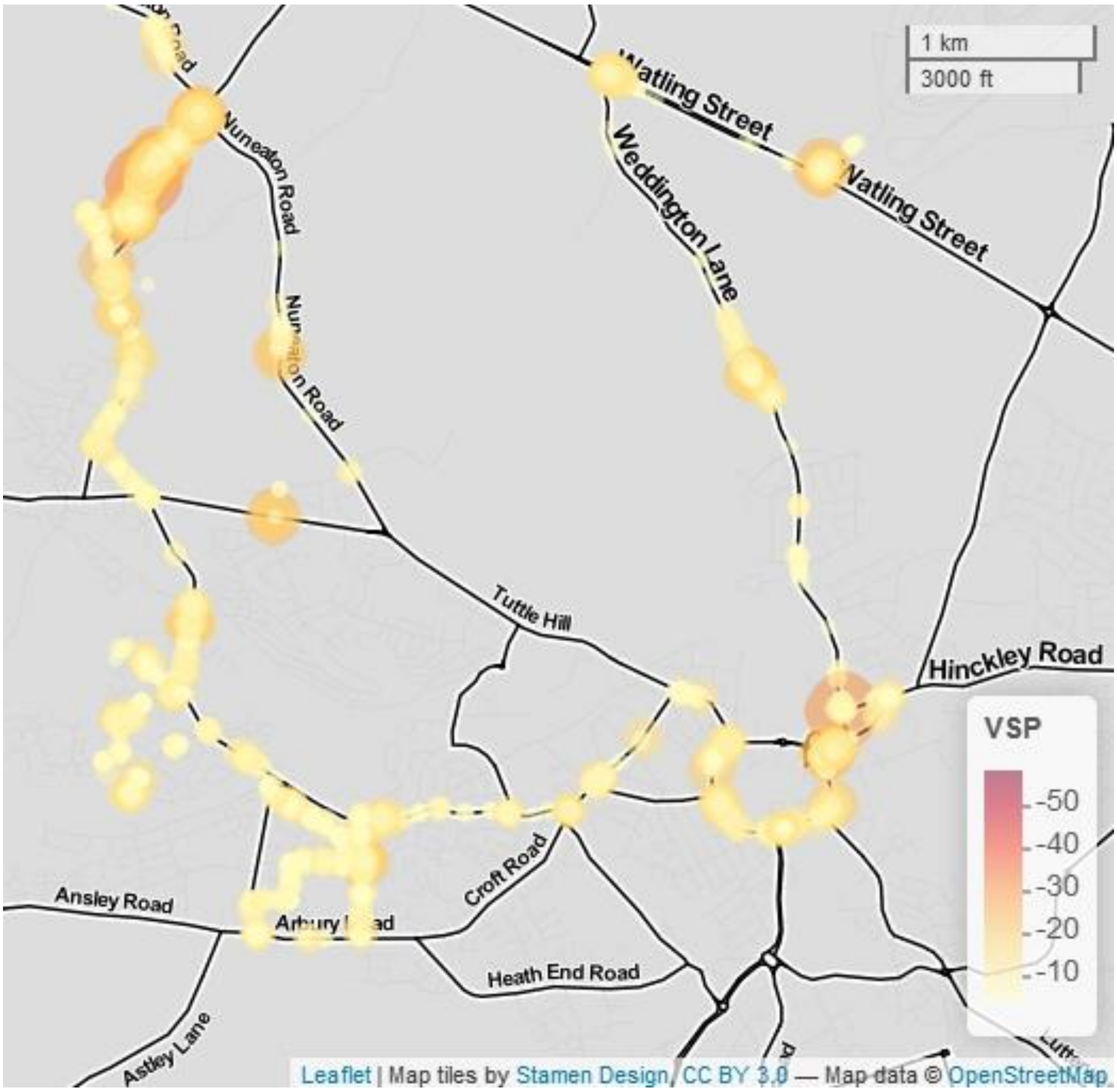


Figure 15 Visualisation of VSP (where VSP is < -5 kW/t) in the urban town of Nuneaton

The mapped brake wear illustrations could also in principle help guide the placement of an ambient measurement site for maximum brake wear emissions. As discussed previously, the siting of air pollution monitoring sites is unlikely to be optimum for detecting brake wear emissions of particulate matter.

4.1.3 Scoping a development to produce a brake wear emissions model

Section 4.1.2, above, has presented an innovative potential approach for demonstrating the typical pattern and likely magnitude of brake use expected in real journeys, to better spatially apportion brake use. This approach showed how spatially variable braking is, which is not reflected well in emissions inventories, and not well-researched to date. This section will present how to apply and develop such a higher resolution understanding of brake use to better inform emissions from brake wear and how this affects ambient PM concentrations at a high spatial resolution.

Underpinning the development of a brake wear emissions model is an understanding of brake use at a high spatial and temporal resolution. The potential approach outlined in section 4.1.2, was based on data from 19 passenger cars tested as part of UK Department for Transport research in 2016. The robustness of this approach is limited by the amount of data used. In order to develop a more robust brake use inventory, it would be beneficial to explore the data available on second-by-second vehicle behaviour and movements, as well as data sets reporting actual brake usage. These additional data sources include euroFOT and the Institute for Transport Studies at the University of Leeds.

The University of Leeds for example, has a large data set from 20 instrumented vehicles as part of a safety project (Intelligent Speed Adaptation, ISA). The data includes the measurement of vehicle speed (at 1 Hz), whether the brake pedal is used and the strength of brake use. Such a data set would help verify the prediction from vehicle speed and road gradient when brakes are in actual use and the strength of their use.

This work would enable the development of traffic-situation specific emission factors that better reflect real driving behaviour. This approach could for example be aligned with the traffic situations used in HBEFA, which is widely used for the calculation of ‘conventional’ emissions from road vehicles such as NO_x and CO.

These traffic-situation specific emission factors could then be applied and run through an air quality dispersion model for urban environments, to assess how the application of more traffic situation specific brake wear emission factors affects PM concentrations. The model would provide estimates of the spatial distribution of PM concentrations from brake wear and information on the source apportionment. Furthermore, an air quality dispersion model could be used to compare current approaches to estimating brake wear emissions and concentrations with a more refined approach.

4.2 Emissions for future vehicle and brake technologies

4.2.1 Overview of current brake system technologies and brake wear rates

Different rates of brake wear will occur for different vehicle types and different brake systems:

- Different vehicle types
  - Passenger cars,
  - Light commercial vehicles
  - Rigid HGVs
  - Articulated HGVs
  - Their trailers
  - Buses and coaches

- Different types of brake systems
  - Disc brakes
  - Drum brakes
  - Hydraulically applied brakes
  - Air brakes

These are likely to affect PM emissions from brake wear in different ways and understanding how would help to understand how emissions have evolved in the past, how emissions may vary in different locations according to where vehicles operate and will help to predict how changes in future technologies will change PM emissions in the future.

The purpose of this section is to elaborate on these technologies and how they could affect PM emissions from brake wear. The future and emerging technologies are considered in terms of their opportunities to reduce PM emissions. This has led to a scoring system based on the likelihood of their uptake on different vehicle types and the likelihood of their impact on reducing PM emissions.

It has been noted that the materials used to construct the brake systems are important when considering particle emissions from brake wear. Both disc rotors and the drums (part of the rotating wheel onto which disc pads are applied) tend to be made from cast iron. Some disc rotors in the higher performance passenger cars use reinforced carbon-carbon ceramic matrices, composites and aluminium. Disc pad material, a major component of the brake wear material, generally comprise five main components: binders, fibres, fillers, frictional additives or lubricants and abrasives. Asbestos was used historically, but is no longer used.

A review on brake wear particle emissions (Grigoratos & Martini 2015) cites around 120 references. It contains a section reviewing the composition of brake linings in terms of the materials currently used. This is summarised in Table 3, using the range of composition values taken directly from Grigoratos and Martini (2015).

Table 3 Composition of brake linings, taken from review of Grigoratos and Martini (2015).

Main component	Fraction of brake lining	Materials used
Binders	20% - 40%	Modified phenol-formaldehyde resins
Reinforcing fibres	6% - 35%	metallic, mineral, ceramic or organic: mainly copper, steel, brass, potassium titanate, glass, organic material and Kevlar
Fillers[7]	15% - 70%	barium and antimony sulphate, magnesium and chromium oxides), silicates, ground slag, stone and metal powders
Frictional additives or lubricants	5 – 29%	Graphite
Abrasives	~10%	Aluminum oxide, iron oxides, quartz and zircon

Brake linings can be categorised by their reinforcing fibres, according to:

- non-asbestos organic (NAO)
- semi-metallic
- low metallic

From reviewing studies looking at the elemental composition of brake wear, as reported in Table 3 within the review by Grigoratos and Martini (2015), the major metallic constituents are:

Iron	1,300 – 637,000 ppm
Copper	70 – 210,000 ppm
Titanium	100 – 110,000 ppm
Aluminium	330 – 20,000 ppm

The same review (Grigoratos & Martini 2015) gave data on the concentrations of a further 16 metals, including most of the first row transition metals as well as tin, lead, zinc sodium and potassium.

This overall, holistic picture is important because brake wear rates and compounds from the whole of road transport is **the sum of the wear from all vehicles.**

It needs to be considered that the braking systems in vehicles, especially passenger cars, have changed considerably over the last three decades. Specific areas include:

- For passenger cars, going from driver generated pressure to engine assisted braking

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[7] Used to improve thermal and noise pad properties and also reduce the manufacturing cost

- For passenger cars, going from the standard disc brakes on the front and drum brakes on the rear to disc brakes all round
- The use of anti-lock braking software
- Trailers of articulated vehicles going from three 4-wheels per axle to three 2-wheels per axles, reducing rolling resistance, tyre wear, and the number of wheels to which brakes are fitted.
- The change for standard European semi-trailers on going from drum to disc brakes
- The use of semi-trailer braking systems to prevent locking up (ABS) improve stability etc., which mean that trailers can brake more rapidly, safely.
- Unseen changes in the materials used in brake linings for all types of vehicles from PCs to HDVs and their trailers.

An important conclusion from the above list is that **braking systems, and consequently brake wear rates, have changed significantly during recent decades**. A corollary to this conclusion is that it is very likely that the **historically measured brake wear rates, and the emission factors estimated from these, may no longer be appropriate for current new vehicles**.

In addition to changes in brake systems that have occurred during the past three decades, there are also geographic differences between the braking systems used in different areas of the world. Some aspects of this were discussed in a paper published by the International Forum for Road Transport Technology at the 13th International Symposium on Heavy Transportation Technology, held in Argentina in 2014. In a paper that compared brake systems for European and North-American heavy vehicles[8], the authors conclude that they are significantly different, with the North-American trucks tending to have powerful brakes at the rear, and light brakes for the steering axles. These differences stem from fundamentally different brake design philosophies, which are then translated into different brake regulations for the two geographic locations. An important conclusion from these differences is that quantitative measurements of brake wear emissions may systematically vary dependant on the regulations the vehicle(s) tested were manufactured to meet.

4.2.2 Opportunities to reduce particle emissions from brakes

From the above considerations combined with the comments from the manufacturers of brake systems, the following list of opportunities to reduce particle emissions from brakes was drawn up:

1. Initial system specification – making sure that the pad work rate, disc work rate and disc temperature rise is correct or optimised for each vehicle (sub-)model;
2. Optimising the choice of brake-pad friction material;
3. The use of carbon ceramic discs to replace cast iron discs;
4. Efficient cooling of the disc through ducting, optimised surface area and efficient vane design
5. Larger wheel envelopes to maximise pad area;
6. The best utilisation of regenerative braking;
7. Positive piston (brake-pad) retraction on both sides of the brake disc – reducing drag and off-brake wear;
8. Brake-by-wire to disconnect pedal feel and increase brake-pad to disc clearance

It is noted that the list above contains potential changes to both the brake discs, and the brake pads. Items 1, 2, and 4 can be viewed as on-going incremental changes that involve further optimisation of the systems and materials already being used. Item 7 is an adaptation/ extension of existing technologies. In contrast, Items 3, 5, 6 and 8 are more fundamental changes in technology. Some further comments on changes in automotive technologies that will impact on brake wear are given below. The sub-titles provide a link between the technology discussed and specific items listed above.

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[8] International Forum for Road Transport Technology at the 13th International Symposium on Heavy Transportation Technology, held in Argentina in 2014. Paper entitled: “Brake system comparison for European and North-American heavy vehicles, wear particle emissions”: P Hart and L Bruzsa, http://road-transport-technology.org/conferenceproceedings/2014-hvtt13/

The opportunities for these technologies to reduce PM emissions have been considered through the development of a scoring system summarised in the next section based on our **expert judgement** on the likelihood of their uptake on different vehicle types and the likelihood of their impact on reducing PM emissions.

4.2.2.1 Light-weighting - affecting brake system specification, Item 1

Pressures on manufacturers of passenger cars to improve fuel economy, principally exerted through the EC regulations on reducing CO_2 emissions, promote vehicle light-weighting. Lighter vehicles lead to lower amounts of energy that need to be absorbed by brake systems, and consequently reduced brake wear emissions. However, counter to this trend, safety considerations, vehicle size and comfort considerations generally lead to mass increases, leading to little overall change in vehicle weights for new passenger car models.

For HDVs the opportunities for light-weighting are greater. The current benefit is the potential to carry more cargo for fully loaded vehicles, thereby reducing vehicle-kilometres driven, or the partially loaded vehicle is lighter than its nonlight-weighted baseline truck and uses less fuel. Both scenarios would lead to modest reductions in brake wear emissions. In addition, the European Commission is currently working on regulatory measures to reduce CO_2 emissions.

4.2.2.2 Carbon ceramic discs and larger wheels – Item 3

Carbon ceramic discs are cited as being more durable, giving reduced brake wear, increased life and less brake dust[9]. If these claims are confirmed by increased in-use experience, then switching to carbon ceramic discs would reduce brake wear particulate emissions.

However, carbon ceramic discs are very expensive relative to cast iron standard discs, and are only fitted to premium brands (e.g. Porsche, Bugatti, Lamborghini, Aston Martin, McLaren etc.). Therefore, although it is adjudged to have **the potential** to significantly reduce brake particulate emissions it is anticipate that in practice this technology will have only a small penetration into the market, and only a minimal impact. Consequently, in the summary given in section 4.2.3, this technology change is given a score of 2 (out of a maximum of 5) for passenger cars only.

4.2.2.3 Regenerative braking – Item 6

For hybrid and electric vehicles, a significant part of their improved fuel economy at low speed/urban driving occurs because of the harvesting of kinetic energy when reducing speed. These vehicles use their electric drive motors to act as generators during decelerations, a fundamental aspect of their design. The impact of this is to markedly reduce the amount of energy absorbed by the brake systems, and consequently to markedly reduce brake wear emissions.

This reduction in brake wear emissions occurs for all vehicles using regenerative braking, which include hybrid vehicles, plug-in hybrid vehicles, electric vehicles, and hydrogen-fuel cell-electric vehicles.

In terms of vehicle segments affected it has the largest potential for passenger cars, considerable potential for light commercial vehicles and urban buses. The impact of regenerative braking will have the smallest potential for articulated trucks and coaches, which tend to travel longer distances at higher average speeds per trip and brake less.

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[9] Two web available articles extolling the virtues of ceramic discs are given available from: https://surfacetransforms.com/white-papers/2013/5/22/top-10-faqs-on-ceramic-brakes-pads-and-carbon-ceramic-material and https://www.sglgroup.com/cms/international/products/product-groups/cc/carbon-ceramic-brake-disks/index.html?__locale=en

4.2.2.4 Positive piston retraction – Item 7

Systems are being developed that retract the brake pads from both sides of the brake disc. This both reduces drag slightly when the brakes are not applied, and reduces off-brake wear. However, whilst this has the potential to reduce particulate emissions from brakes, it is not known what the fraction of off-brake to on-brake wear is. The nature of the brake-wear (per km), as a function of speed, appears to be principally determined by the average number of brake applications at different speeds and shows little evidence that off-brake wear is very significant. For this reason, the potential scope of this measure is anticipated to be small, and is given the low score of 1 in the summarising table below.

4.2.2.5 Brake-by-wire – Item 8

Many aspects of modern road vehicles are now control-by-wire – the accelerator pedal being one of the obvious changes that has occurred as vehicle fuelling has become more sophisticated, and under computer control, and electrical actuation. Braking-by-wire is being used in high performance vehicles, and it is anticipated this will roll-out to other vehicle types in the future.

The application of brakes can be categorised into critical braking, where braking is most severe and is used to avoid, or reduce the impact energy, in a crash, and non-critical braking. The industry anticipates that for non-critical braking, i.e. the majority of brake applications, the use of brake-by-wire systems may lead to much more even brake pad wear. This would have the advantage of reducing the need for brake pad replacement. It is also assumed that the rate of braking would be optimised for the deceleration required, with the algorithms determining the optimal degree of brake application. It is this optimisation that is anticipated will lead to reduced emissions of brake wear particulate emissions. However, the extent to which this may happen has yet to be quantified.

4.2.3 Summary of opportunities to reduce particle emissions from brakes, and the vehicle segments to which they apply

The information given in the preceding sub-sections is gathered together and summarised in Table 4. This both provides a semi-quantitative assessment as to the potential impact of the eight opportunities listed at the start of Section 4.2.2, and considers how these opportunities might apply to the different vehicle categories. A scale of 0 – 5 is used where:

0	denotes that it is unlikely this opportunity will be relevant to this vehicle segment
1	denotes that minimal reduction in particulate emissions might occur from this opportunity
4 and 5	denote that these opportunities represent the most significant potential for reducing particulate emissions from brake wear in the future based on likely uptake and their effect on emissions.

A less detailed assessment is provided by the cell colour, with white cells denoting little to no anticipated reduction in particulate emissions from opportunities, lighter green denoting modest anticipated reduction in particulate emissions and the deepest green denoting the opportunities anticipated to provide the largest reduction in brake wear particulate emissions.

Table 4 Summary of the anticipated reduction in brake wear particle emissions from different opportunities applied to different vehicle segments

Potential change	Passenger cars	Light commercial vehicles	Rigid lorries	Articulated lorries	Buses and coaches
1 System specification – light-	1	1	2	2	2

weighting					
3 Carbon ceramic discs	2	0	0	0	0
5 Larger wheel envelopes	1	1	1	1	1
6 Regenerative braking	5	4	2	1	4
7 Positive piston retraction	1	1	1	1	1
8 Brake-by-wire	2	2	2	2	2

The purpose of this scoring system is to highlight where reductions in brake wear emissions are likely to occur in future, on what vehicle types and over what timeframe. This could be used to prioritise where further research into brake wear emissions should be made. The table indicates that inventories of PM emissions should pay particular attention to changes in brake wear emissions from light duty vehicles and buses using regenerative braking, taking account of their likely uptake into the fleet. Although this analysis does not indicate the extent by which brake wear emission factors might change from these systems, it does show that future research should focus on measurements of brake wear emissions from hybrid and electric vehicles with regenerative braking as well as more conventional technologies currently in the fleet.

5 Conclusions

In **task 1**, a critical review of the scientific literature aimed at quantifying the contribution of brake wear, and other traffic-related sources, to concentrations of Particulate Matter (PM) was undertaken, to establish the current evidence base. Over 30 scientific articles were reviewed, and around 2/3 of these were published after 2012. Section 2.2 show the results of source apportionment studies, to give a sense of the contribution of road traffic to concentrations of PM in the air. This showed that road transport contributed a considerable proportion to concentrations of PM in the air, and that this contribution is highly spatially and temporally variable. Section 2.3 focused on literature estimates of the contribution of the brake wear component of road traffic to concentrations of PM in the air. This showed that there were few articles that explicitly provided an estimate of the contribution of the brake wear to concentrations of PM in the air. Of the studies that did provide estimates, the contribution of brake wear ranged from around 5-10% of the PM_{10} concentrations in busy urban roadside areas (~0.8 $\mu g\ m^{-3}$ to 4 $\mu g\ m^{-3}$). At quiet rural roads, the contribution would likely be much less, and for context, the contribution of brake wear to the UK's national inventory estimates of PM_{10} emissions for the year 2015 was 1.7%. An estimated contribution of 11% was also provided for measurements made in a motorway tunnel. An important finding from this section was that the literature shows that there are considerable uncertainties in estimating the contribution of brake wear to ambient PM concentrations. How these uncertainties could be reduced was covered in section 4.1.

Task 2 considered brake wear contributions according to national emission inventories. This introduced the basis of how brake wear emission inventories are developed and the emission factors used in the UK's National Atmospheric Emissions Inventory. This showed that the highest brake wear emission factors were found on urban roads and for the heavier duty vehicles. In this task, national inventory data for $PM_{2.5}$, reported by the UK and Germany in the latest year and projected to 2030, was also analysed. This was to show how emissions from different sources (including brake wear) compare now and in the future. This showed that non-exhaust emissions are expected to increase slightly from 2015 to 2030 whilst exhaust emissions are expected to decrease dramatically. Taking the UK as an example, the inventories suggest the contribution from exhaust sources of $PM_{2.5}$ will decrease from 43% of all road transport emissions in 2015 to 7% by 2030. This suggests that road transport exhaust emissions will have only a minor contribution in the future and the focus for road transport emissions abatement may well be better placed on non-exhaust emissions, if needed.

In **task 3**, a scoping study was undertaken into how uncertainties in brake wear emission estimates can be reduced, and their contribution to PM air pollution can be reduced (section 4.1). This section describes how a 'brake use inventory' could be developed to provide a better estimate of where brakes are used. This section also describes the work that would be needed to inform this, including: making high temporal resolution measurements of metal tracers and contacting industry to obtain better data on the composition of brake pads used in Europe. As well as this, air quality measurements submitted to the European Environment Agency to satisfy air quality directives were reviewed. It was found that there was data available for the brake wear tracers copper and iron but not for antimony or barium. It was also found that there was no data of a higher temporal resolution than daily-averaged mean concentrations.

A further part of task 3 lays out a modelling approach to improve the understanding of the contributions of brake wear related compounds to ambient concentrations of PM_{10} and $PM_{2.5}$ in the context of daily and annual mean concentration limits (section 4.1.2). High resolution, publicly available data from real vehicle journeys was analysed to develop a proxy for braking; negative Vehicle Specific Power (VSP). This was mapped using open source software to demonstrate the typical pattern and likely magnitude of brake use expected in real journeys, to develop a better understanding of brake use spatially. Selected images from these maps were presented and discussed. This demonstrated that the pattern of negative VSP versus exhaust NO_x emissions was anti-correlated, as expected. This analysis also showed that the highest intensity braking was seen at motorway exit/slip roads. Section 4.1.3 then describes how this approach could be applied and developed to better inform emissions from brake wear and how this affects ambient PM concentrations at a high spatial resolution.

A further part of task 3 considered brake wear emissions from future vehicle technologies (section 4.2). An important conclusion from section 4.2 was that braking systems, and consequently brake wear rates, have changed significantly during recent decades. A corollary to this conclusion is that it is very likely that the historically measured brake wear rates, and the emission factors estimated from these, may no longer be appropriate for current new vehicles. The future and emerging technologies were also considered in terms of their opportunities to reduce PM emissions. This led to a scoring system, developed from our expert judgement, based on the likelihood of their uptake on different vehicle types and the likelihood of their impact on reducing PM emissions. This was to highlight where reductions in brake wear emissions are likely to occur in future, on what vehicle types and over what timeframe. This could be used to prioritise where further research into brake wear emissions should be made. The scoring system table indicates that inventories of PM emissions should pay particular attention to changes in brake wear emissions from light duty vehicles and buses using regenerative braking, taking account of their likely uptake into the fleet. Although this analysis does not indicate the extent by which brake wear emission factors might change from these systems, it does show that future research should focus on measurements of brake wear emissions from hybrid and electric vehicles with regenerative braking as well as more conventional technologies currently in the fleet.

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The Gemini Building
Fermi Avenue
Harwell
Didcot
Oxfordshire
OX11 0QR
United Kingdom

t: +44 (0)1235 753000

e: enquiry@ricardo.com

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Behrenstraße 35
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