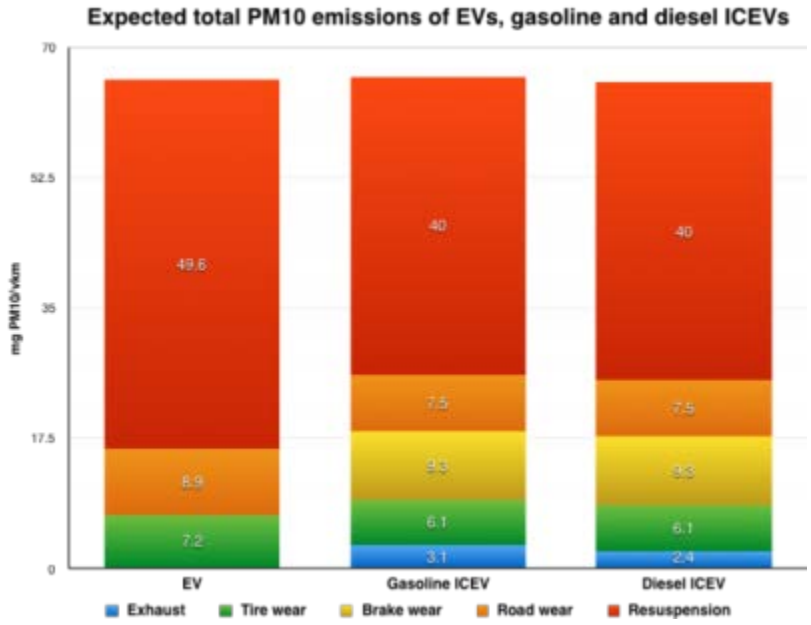
Non-Exhaust Emissions from EVs: A "Sleeping Giant Issue"?

December 2016 Report to Clients

Earlier this year an interesting study came across my desk on the impact that non-exhaust emissions from EVs have on air quality, and in particular, particulate matter (PM). And it was interesting enough for me to actually purchase it and read about the findings. They were surprising to me: when factoring in the additional weight from EVs and non-exhaust PM factors, the authors found that total PM10 emissions from EVs were equal to those of internal combustion engines vehicles (ICEVs), as shown in the chart below. And they weren't much better for PM2.5, nearly equal to diesel. I decided to investigate further.



About Non-Exhaust Emissions

Non-exhaust emissions are generally related to wear and include tire wear, brake wear, road surface wear and resuspension of road dust, according to an article posted earlier this year in Green Car Congress:

- Tires generate particles both through the wear of the rubber and through the wear of road surfaces. These processes may depend on tire type, size, and age, vehicle speed

and weight, road surface properties, and meteorological conditions (temperature, road wetness, etc.). Tire wear contributes to PM10 even though most of the wear results in larger particles.

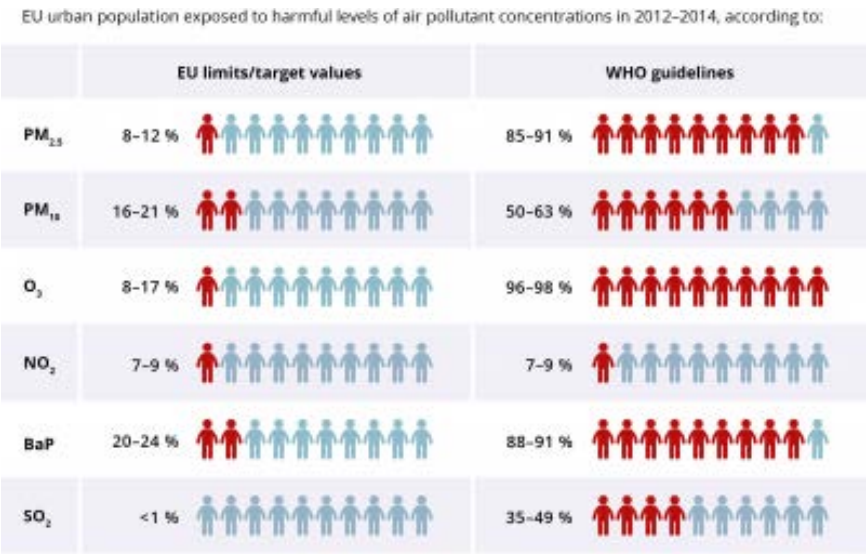
- Brake wear is due to large frictional heat generation by brake linings. Detailed laboratory tests have shown that 50% of the total wear is emitted as airborne material; the other half directly deposits on the (road) surface and the wheel of the car.
- Wear of the road surface varies significantly based on the properties of the asphalt as well as tire type, vehicle type, and speed, as well as road surface conditions.
- Road wear—pavement-derived PM10—mainly consists of small mineral fragments and therefore is dominated by crustal elements like Si, Ca, K, Fe, and Al. The composition therefore differs depending on the rock material used.

There is more than 15 years of research showing that the contribution of non-exhaust primary particles to the total traffic generated primary particles is significant in urban areas. As we all know, exhaust emissions are regulated in many countries around the world, and in major markets ever more stringently, but non-exhaust emissions are not. It's proven a difficult task as the authors highlight:

> …"[B]ecause of the chemical differences between non-exhaust and exhaust emissions, they result in different secondary PM. Secondary PM is formed in the atmosphere through chemical reactions, rather than being directly emitted by a source. The volatile organic compounds in exhaust gases react with sunlight in the atmosphere to form secondary organic aerosols (SOAs) whereas non-exhaust emissions are mainly inorganic and therefore form secondary inorganic aerosols (SIAs). However, it is exceedingly difficult to model SOAs and SIAs emissions. Not only do many studies have difficulty determining the fractional contribution vehicles make to SOAs, but it is also problematic to differentiate between primary and secondary PM."

PM Pollution in Europe…and Elsewhere

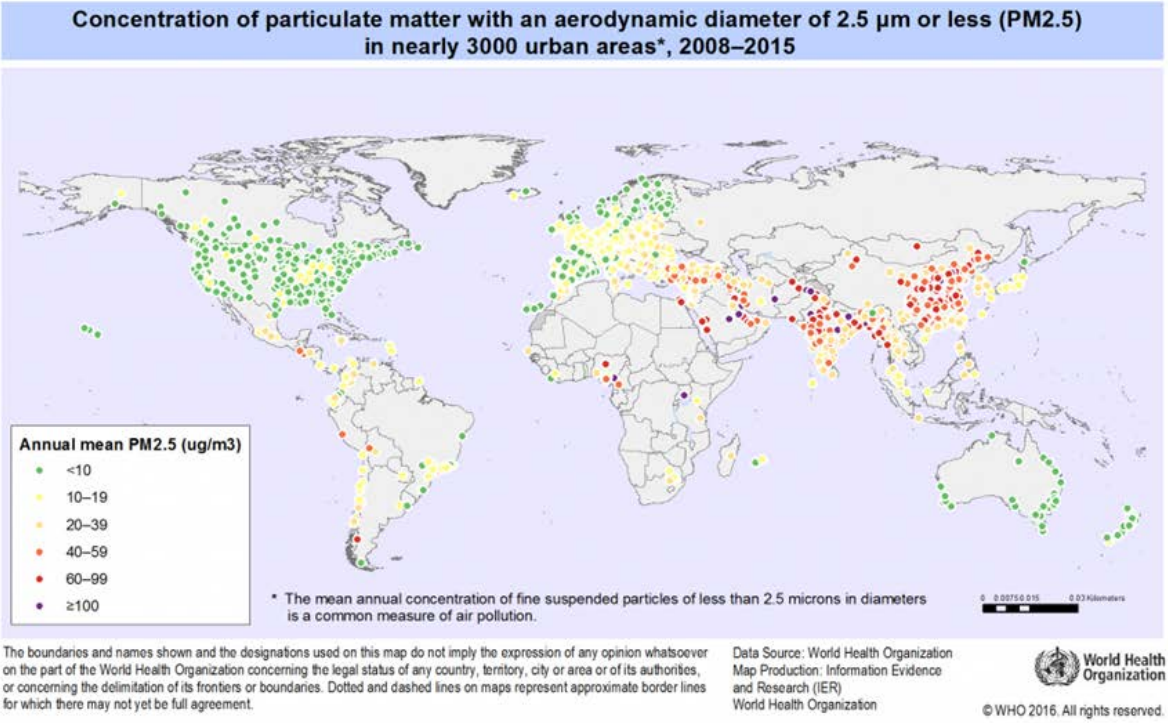
The fact that non-exhaust emissions could be a major issue for EVs in Europe (and elsewhere) is huge. First, PM pollution is a major issue in Europe. The European Environment Agency (EEA) released its annual report on air quality in Europe just a few weeks ago. As I highlighted in a recent post, exposure to PM2.5 was responsible for about 467,000 premature deaths in 41 European countries in 2013. Within the EU, premature deaths exceeded 430,000. The following graphic shows EU urban population exposure to harmful levels of air pollutant concentrations, including PM, between 2012-2014 under both EU targets and World Health Organization (WHO) guidelines.



Europe is not the only region struggling with air pollution and mitigating PM emissions. It's a problem around the world, as the figure below from the World Health Organization (WHO) shows, especially in major or mega cities with a high concentration of urbanization and vehicles.

Particulate Matter Pollution Getting Worse

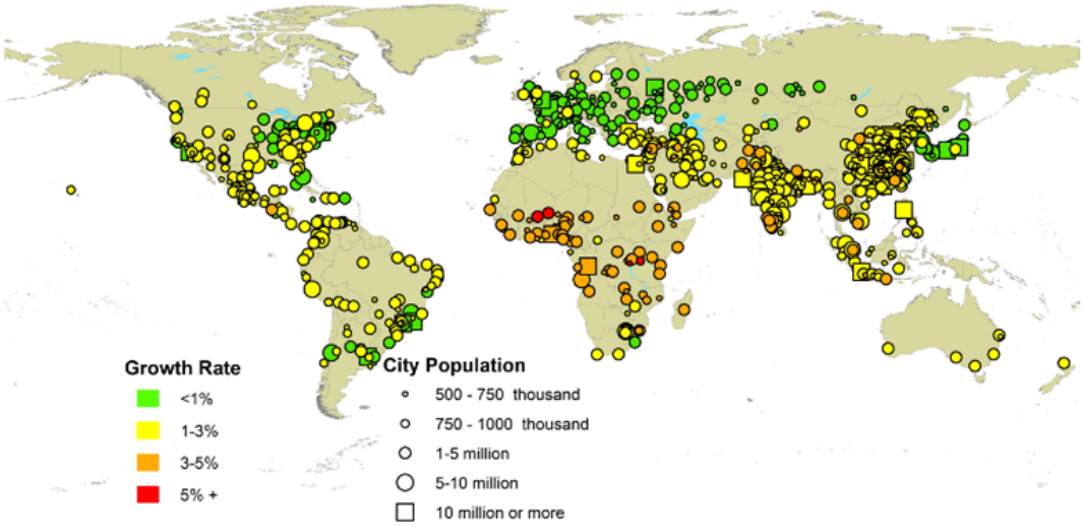
Affects Emerging and Western Economies; Cleaner Fuels, &Vehicles Were Not Enough to Solve the Issue



The urbanization trend is going to continue. According to the UN, 54.5% of people live in urban areas, increasing to 70% by 2030. The figure below from the UN shows the urbanization rate from 2014-2030.

Global Population Density in Urban Areas

54.5% of People Live in Urban Areas, Increasing to 70% by 2030; Traffic and Air Pollution are Becoming Unmanageable



Note: Designations employed and the presentation of material on this map do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries.

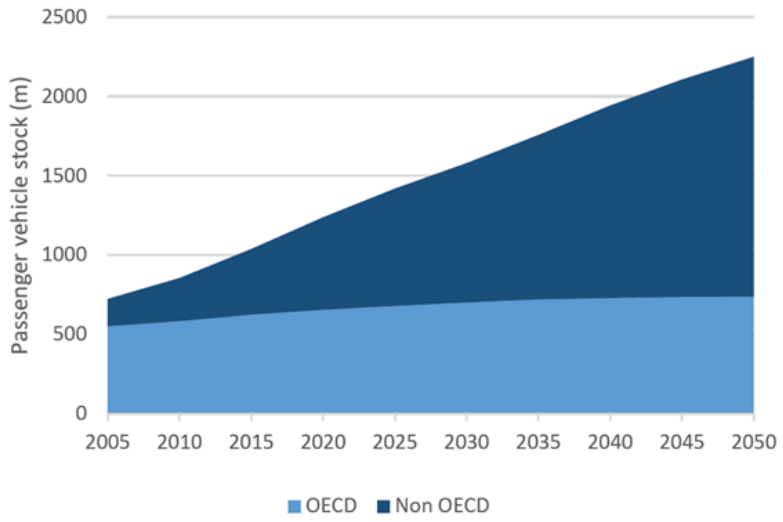
- With a growing fleet, managing traffic is becoming a more serious challenge to cities, and so is air pollution as a result
- Some cities will bank on improved public transport and connected, autonomous car sharing through EVs to manage it, though calling for car-free days or car bans in city centers, affecting future demand for fuels.

And vehicle sales are going to continue to grow as well — enormously in some areas of the world. While vehicle sales will flatten in OECD countries, they will take off in the non-OECD countries, as the figure below shows. According to the OECD, vehicle sales will grow 135% through 2050, with 90% of the growth coming from non-OECD regions such as Asia, Latin America and Africa.

Car Sales Are Expected to Grow Globally

Different Opinions on How Much EVs Will Penetrate the Fleet

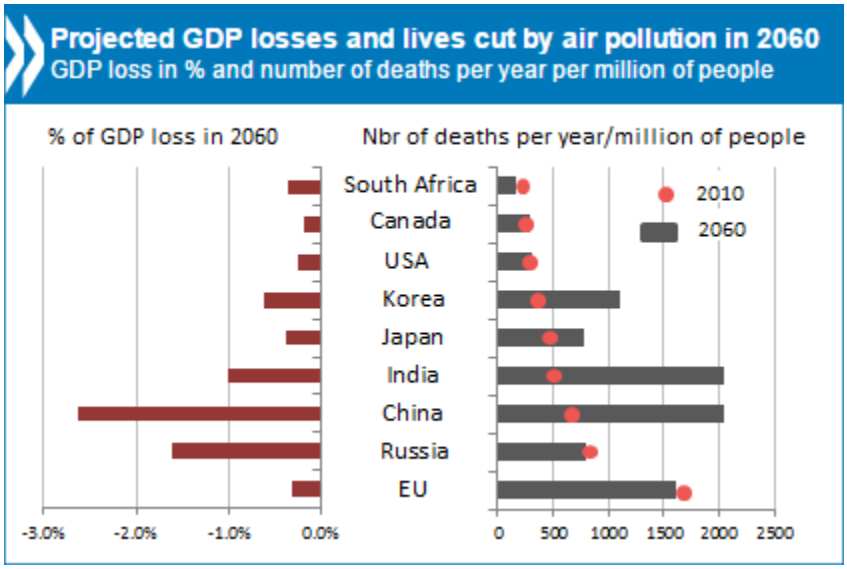
FIGURE 1 Global passenger light duty vehicle stock out to 2050



- Global fleet expected to grow 135%+ through 2050, and 90% of this growth will come from non-OECD countries lead by Asia, Latin America and Africa
- No question that ZEVs will make up a significant part of the fleet, but penetration will depend on policies, incentives and consumer awareness/preference

The air pollution issue, most critically PM, is only going to get worse in the coming years. The Organization for Economic Cooperation and Development (OECD) released a report earlier this year assessing the potential economic impacts of spiraling air pollution through 2060, finding 1% loss of GDP or $2.6 trillion annually in losses. The impacts are attributed in part to premature mortality, illness and medical expenses, lost productivity and lower crop yields.

As the following chart from a recent post shows, the GDP losses by 2060 are substantial in the EU. But, more alarming is the projected number of deaths, which is *second* only to China and India. The figure below from the OECD shows projected GDP losses and deaths per million people by 2060.



Source: OECD

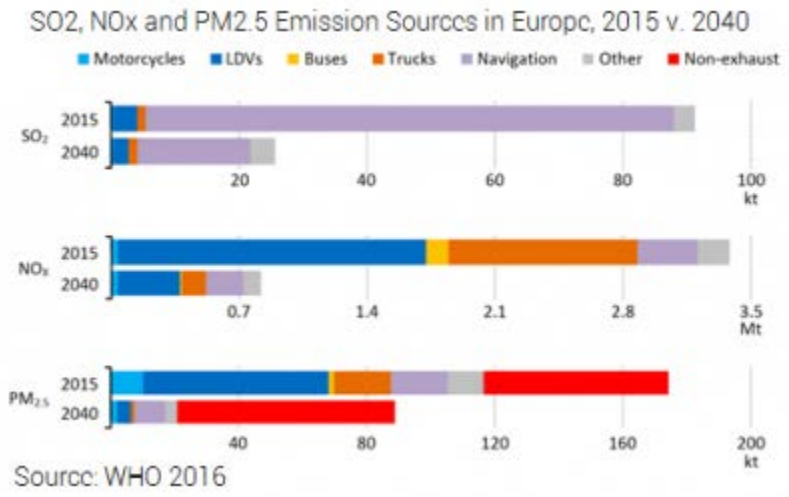
A UNICEF study released recently found that almost 300 million children live in areas around the world with the most toxic levels of outdoor air pollution – six or more times higher than international guidelines set by the World Health Organization (WHO). Another 2 billion children, including those in developed regions such as North America and Europe, live in areas where outdoor pollution exceed WHO guidelines (shown in the figure below). PM was a major pollutant cited. The culprits: vehicle emissions, heavy use of fossil fuels and waste burning.

As urbanization, the vehicle fleet and consequently air pollution increases, countries and cities around the world have been looking for ways to mitigate air pollution. For example, policymakers in the Netherlands and Germany have talked about banning the ICEV. The mayors of four world cities (Paris, Madrid, Athens and Mexico City) are planning to ban diesel vehicles, while the mayor of London is looking to set new limits on their use in the city. Five African countries recently banned "dirty" diesel fuel because of high PM air pollution.

Other cities are trying to coax their citizens out of vehicles and are working to improve public transport as well as promote biking and walking lanes. Officials in the Miami, Florida area are so exasperated they have decided to let traffic worsen in an attempt to promote public transport, walking and biking in the city. Some are also promoting ride sharing services.

In Europe, non-exhaust emissions are already a significant source of PM2.5 emissions and that will remain the case through 2040 as other vehicle-based sourced decline, according to WHO. In fact, the figure below shows that PM2.5 emissions will be dominated by non-exhaust emissions. WHO noted: "Non-exhaust emissions are very significant in transport, relating to emissions from the abrasion and corrosion of vehicle parts (e.g., tires, brakes)

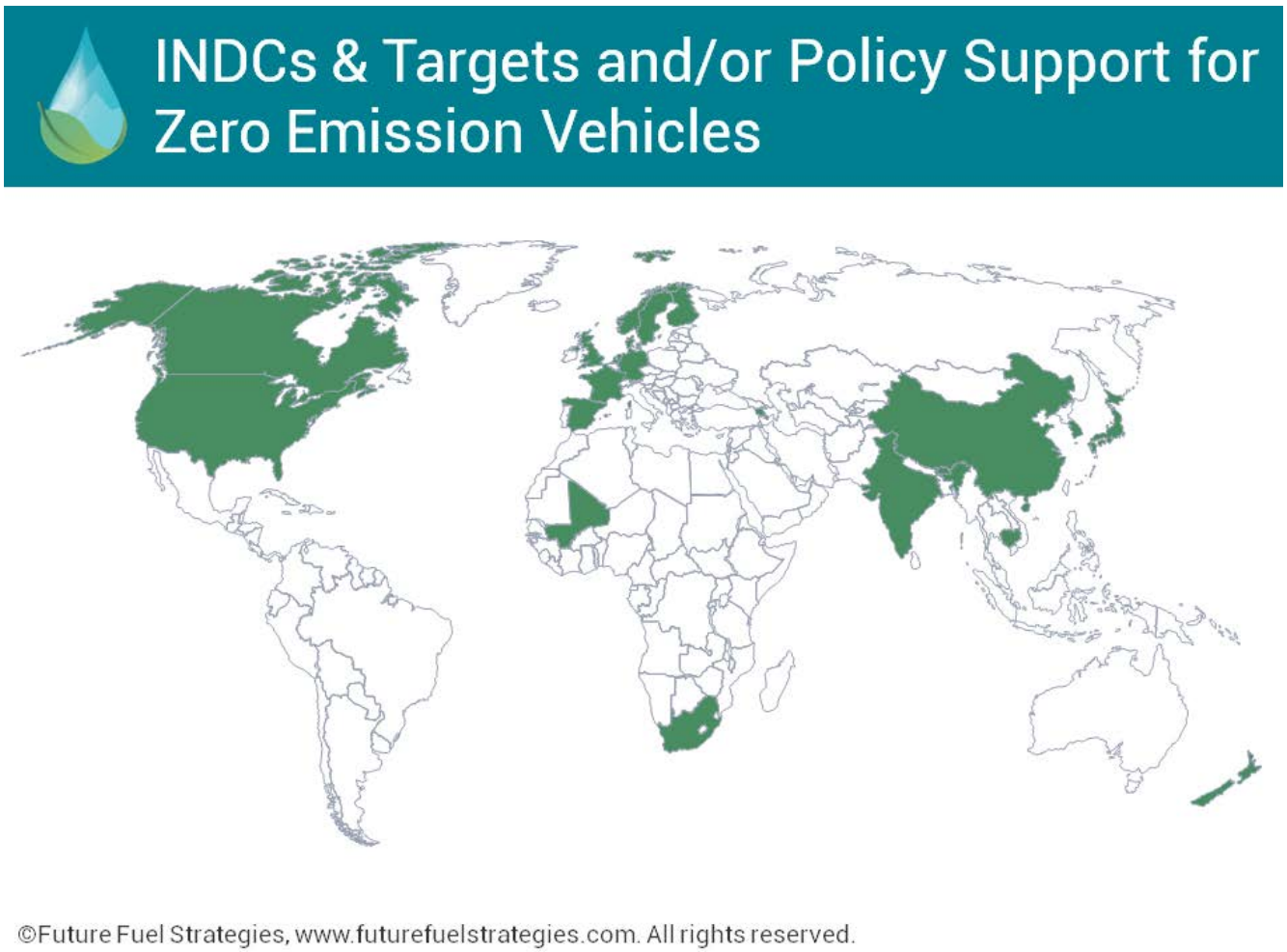
and road surfaces, and are (in many cases) still relevant for those vehicles that have no exhaust emissions."



EVs to the Rescue?

It's hard for people to give up personal mobility, especially when public transport isn't available, practical or effective. Biking and walking in some parts of the world can be downright dangerous. And having a personal vehicle is very much a status symbol in many countries. It's also hard for policymakers to take away their citizens' personal mobility as well — not without risking paying the political price. But zero emission vehicles (ZEVs) present a solution: Personal mobility that reduces both GHGs and air pollution. EVs in particular have been strongly touted as a (or even "the") policy solution that solves this knotty transport problem.

Over the last few years there have been questions of whether EVs, especially if powered from traditional non-renewable sources (e.g. coal and natural gas), reduce GHGs at all. That issue continues to be debated, and is not the focus of this report. And it's largely irrelevant because policymakers *have* decided these vehicles *do* mitigate climate change. As a result, they are beginning to set policies that encourage and even require ZEVs. As the following figure shows, this is expected to continue as countries implement GHG-mitigating measures under the Paris Agreement. The agreement calls for countries to set Intended Nationally Determined Contributions (INDCs) for GHG mitigation, which include transport mitigation measures such as promoting or requiring ZEVs.



More specifically, the state of California has implemented a ZEV requirement that nine other U.S. states are following: Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. The California program requires for 1.5 million ZEVs in California by 2025 and establishes several milestones on the pathway toward this target. The province of Quebec and China intend to implement similar mandates over the next few years. I expect this trend to continue. Other countries offer incentives for ZEV uptake which are summarized in the figure below.

Table 1 • Summary of policy support mechanisms for EV uptake in place in selected countries in 2015

	EV purchase incentives				EV use and circulation incentives				Waivers on access restrictions			Tailpipe emissions standards		
	Rebates at registration/sale	Sales tax exemptions (excl. VAT)	VAT exemptions	Tax credits	Circulation tax exemptions	Waivers on fees (e.g. tolls, parking, ferries)	Electricity supply reductions/exemptions	Tax credits (company cars)	Access to bus lanes	Access to HOV lanes	Access to restricted traffic zones*	Fuel economy standards/regulations including elements	Road vehicles tailpipe pollutant emissions standards	Market share of electric cars in 2015
Canada													Tier 2	0.4%
China													China 5	1.0%
Denmark													Euro 6	2.2%
France													Euro 6	1.2%
Germany													Euro 6	0.7%
India													Bharat 3	0.1%
Italy													Euro 6	0.1%
Japan													JPN 2009	0.6%
Netherlands													Euro 6	9.7%
Norway													Euro 6	23.3%
Portugal													Euro 6	0.7%
South Korea													Kor 3	0.2%
Spain													Euro 6	0.2%
Sweden													Euro 6	2.4%
United Kingdom													Euro 6	1.0%
United States													Tier 2	0.7%

Legend:	
	No policy
	Targeted policy **
	Widespread policy***
	Nationwide policy
	General fuel economy standard, indirectly favouring EV deployment
Euro 6	Pollutant emissions standard in place in 2015

Notes:
* Such as environmental/low emission zones.
** Policy implemented in certain geographical areas (e.g. specific states/regions/municipalities), affecting less than 50% of the country's inhabitants.
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Source: Clean Energy Ministerial, June 2016

Several U.S. states offer similar incentives: Georgia, Washington, Hawaii, Oregon, Vermont, Colorado, Maryland, Connecticut, New York and Massachusetts.

These policies combined with the decreasing cost of the technology (including batteries) and the extension of range have lead to the growth in EV sales, shown in the figure below. More than 500,000 units were sold in 2015, a 67% increase over 2014. While a small percentage of overall global car sales, the growth in the last five years has been astounding, and some proponents are intent on this trend continuing. From the Zero Emission Vehicle Alliance, to the Clean Energy Ministerial and even the California Air Resources Board the goal is clear: get as many EVs on the road as quickly as possible and end the era of the internal combustion engine vehicle (ICEV).

Electric Vehicles Penetration into the Global Fleet Growing Precipitously

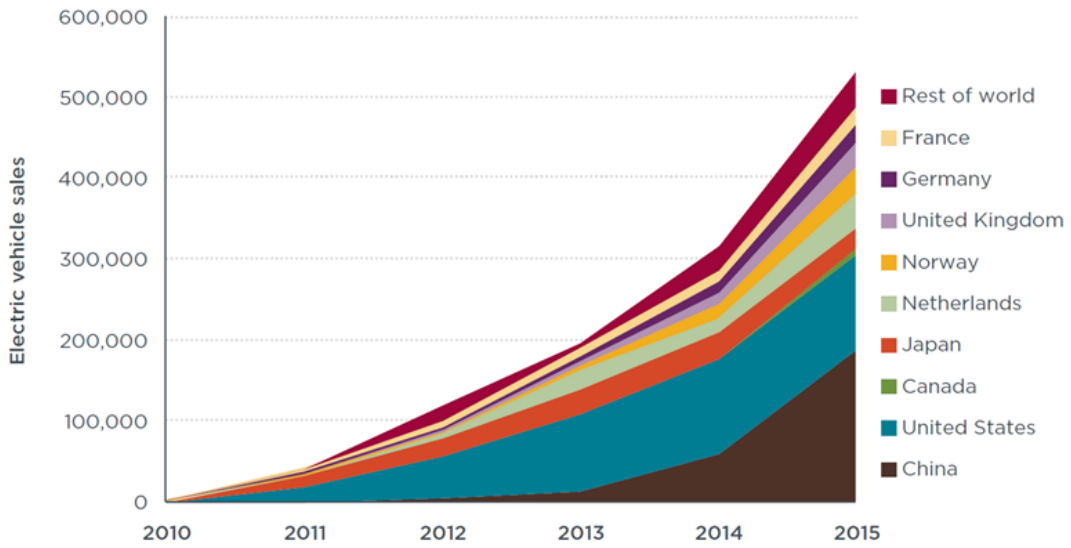

Figure 1. Annual electric vehicle sales globally through 2015

- European and Asian markets have especially shown dramatic EV growth most recently, surpassing North America's electric vehicle sales in 2015
- Electric vehicle market growth through 2016 has almost entirely been in automobile markets with substantial regulatory policy and financial incentives in place

Study Findings on Non-Exhaust Emissions from EVs

One of the key issues in the study is vehicle weight. In the study, the authors analyzed the existing literature on non-exhaust emissions of different vehicle categories, and found that there is a positive relationship between weight and non-exhaust PM emission factors, though they noted that more study in this area is needed. Vehicle weight is increasing for both ICEVs and EVs. The authors found that EVs were 24% heavier than equivalent non-electric models.

In analyzing and comparing both PM10 and PM2.5 emissions from EVs and gasoline and diesel ICEVs, the authors included exhaust emissions, tire wear, break wear, road wear and resuspension. Exhaust emissions, as we know, are non-existent for EVs. With respect to the remaining factors, the authors extrapolated emission factors from other studies in the literature review. For brake wear, the authors assumed a conservative estimate of zero. They assumed a linear relationship between weight and resuspension, and used a 24% increase in resuspension for EVs (due to the on average 24% increase in weight).

The authors reviewed the literature on non-exhaust emission factors for average tire wear, brake wear, road wear and resuspension for ICEs and then compared those factors to EVs, as the chart below shows.

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

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

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

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

Source: GreenCar Congress, citing Timmers and Achten, 2016

Source: GreenCar Congress, citing the study, April 2016

Criticism

As the paper (which was peer reviewed) began to receive media attention, the reaction from EV advocates was swift (and the trolls merciless). Much of the online trolling had no basis in fact, and it's clear from a reading of the comments that most did not read the study. However, some EV experts and enthusiasts took the authors to task on several issues. I researched and collected those issues, particularly those I thought had some credibility, and asked the authors about it. They responded as follows:

- **Issue**: The authors assumed heavier cars with same shape resuspend more (in other words, authors simply assume the issues are weight-related with no supporting research). In a similar comment, another expert said that resuspension is not related to weight but more to aerodynamics.
    - **Response**: "If the current fleet of vehicles would be replaced by another fleet, having a higher average vehicle weight, the non-exhaust emissions will be increased. The relationship is at least linear, but can also be stronger, having an exponential of 1.5 or 2.14. We could have used these non-linear relationships, especially since the factor 1.5 is up to now used by the US EPA. Instead, we have assumed the relationship to be linear and stayed therefore on the conservative side." **With respect to aerodynamics**: "We don't understand this. If this would be true then we should make ICEVs with a similar aerodynamics as EVs. A study from Purdue University and the University of Central Florida, while about acoustics, explains the compression and expansion of air in tires, shown in the following figure from the study (Figure 4.2, shown below). Resuspension is caused by the pumping effect in this contact, as can be seen in the following photo [below] driving on a dirt road. The wake is not caused by the vehicle, but by the wheels."

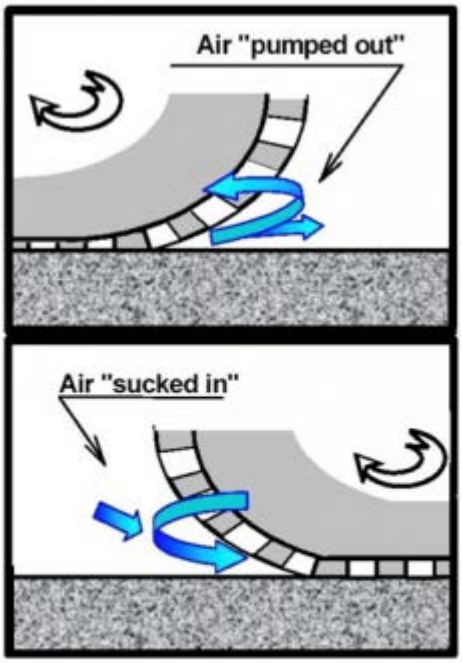

Figure 4.2 Air pumping at the entrance and exit of the contact patch

Source: Purdue University; University of Central Florida

- **Issue**: The authors assume that resuspension (mostly sand) is as bad as NOx and toxins from exhaust.
    - **Response**: "We don't assume or make a judgment whether PM emissions from resuspension are as bad as NOx or other exhaust emissions. We have only limited our research to PM emissions. It is, however, absolutely clear that resuspension is not only sand and there is ample research that documents and gives evidence to the negative health effects of non-exhaust emissions."

- **Issue**: Your high resuspension figures are at least a factor five too high for the Netherlands (and the UK). It's all based on a UK database that one author has access to but there are no peer reviewed publications.
    - **Response**: "The problem with (peer reviewed) papers is that they are specific for a certain type of traffic, or a season, or the influence of studded tires, or the influence of rain. We have gathered a lot of literature on such research. But, in the end, we were not interested in specific situations or circumstances; our intent was to make general conclusions, i.e., time and traffic average emission factors. That is why we believe that emission registrations form governments are so important."

- **Issue**: The authors look at weight and ignore what's in that weight. The implicit assumption is that all particles are created equal.
    - **Response**: "Some critics have said that resuspended emissions are just sand, and that sand is not harmful at all. This is wrong. There are all sorts of particles in the environment, coming from a wide variety of sources. Resuspension or re-entrainment by the tire-road-contact is related to all of these particles; to everything that is accumulated on the road. This is not just sand. U.S. EPA has noted: 'Road dust is earthen material or dirt that becomes airborne, primarily by the friction of tires moving on unpaved dirt roads and dust-covered paved roads. It consists mainly of coarse particles, which in some cases may be contaminated with man-made and naturally-occurring pollutants such as asbestos, mining by-products, animal and human waste, snow and ice control applications (salts) and engine oil.' There are many studies that show the environmental and health risks of resuspended emissions."

- **Issue**: The authors ignore the fact that most EVs use harder compounds to reduce rolling resistance which reduces particulate coming from their own tire wear.
    - **Response**: "We have not seen any research that supports this statement. On the contrary: there are quite a few reports about strong tire wear on electric vehicles."

- **Issue**: EVs will become lighter with each successive generation of battery technology. As BMW has shown, it is possible to drop 1,200 pounds off of a contemporary passenger car, with battery cost savings offsetting part of the light-weighting cost penalty.
    - **Response**: "There is no scientific evidence for this statement. Based on current literature, it can be concluded: larger vehicles have a stronger weight penalty; the weight penalty strongly depends on the size of the battery, i.e., the considered or estimated driving range of a vehicle, and it is generally expected that both BEVs and ICEVs will become or can become less heavy in the years to come. There is however no consensus about the effects of these developments on the weight penalty."

- **Issue**: The least important kind of emissions is that of rubber and road dust created from friction between the road and the wheels. The only dangerous materials that are on the road are residual exhaust particles and braking particles already produced exclusively or primarily by the gassers not the BEVs. That should not count as particle emissions from BEVs. When all vehicles become BEVs there will be none of these particles left on the road. With regard to tire wear which is the only type of emission that BEVs may have that is higher than gassers because of more weight the problem is not analyzed properly. Is rubber dust dangerous for the environment or not and to what degree and how it is related to vehicle weight? These questions are the relevant to study.
    - **Response**: "The environment is much more complicated than this oversimplification…Wheels contribute in several ways to air pollution. Tire and road wear not only cause particles. The contact also grinds larger particles to smaller ones. Moreover, they cause a resuspension of the dust. A tire has a compressed, flat contact area (the so called ground contact patch). Tire deformation and wear is strongly affected by the vertical load, i.e., by the weight of the vehicle. The resuspension is created directly in the contact between the tire and the road. There is a growing number of publications indicating the health concerns of non-exhaust emissions."

Europe's Electro-Mobility Platform also responded to the study putting out a short briefing paper responding to the study which I found ill-fitting and odd considering the study's actual findings. The Platform emphasized in essence that (1) EVs do not emit exhaust PM and (2) both ICEV and EV emit non-exhaust pollution due to braking, both of which were clearly noted and acknowledged in the study (see tables 5 and 6 above). Interestingly though, and to review, the authors assumed a zero value for non-exhaust emissions from braking, while the Platform seems to actually acknowledge this is an issue. The point the study authors were trying to make is that brake wear is an issue, but even if it weren't, non-exhaust PM emissions would still occur and this is something that is worth studying further.

Another study from the team of Hooftman et al. in Belgium that appeared in the open-access journal *energies* earlier this year also analyzed non-exhaust emissions of passenger vehicles, both conventional (diesel and gasoline) or electric, on air quality levels in an urban environment in Belgium. They proposed a method to assess the contribution of EVs to urban air quality in Belgium, compared to conventional vehicles of the same weight class; they modeled the effect on human toxicity, photochemical ozone formation and PM formation. In addition, they simulated disability adjusted life years (DALY) to assess the healthy years lost due to poor urban air quality. The scope of the study was thus not limited to the use-phase of a vehicle. Among their main conclusions were:

- Unregulated non-exhaust emissions have significant and dominant impacts throughout the analyzed categories, and this included EVs.
- However, EVs were the best alternative to diesel and gasoline vehicles across all categories. Hooftman et al. concluded that EVs tend to emit up to eight times less non-exhaust PM than diesel vehicles and at least two times less than gasoline

powertrain, findings which are at opposition to the Timmers/Achten study and others on this topic.

- Non-exhaust emissions require active regulation, a similar conclusion that Timmers/Achten reached. Either this is achieved by using alternative materials during production of both tires, brakes and pavements, or by introducing alternative technologies such as regenerative braking in ICEs to reduce braking wear. Tires should be subject to technological pushes in order to mitigate wear and tire composition.
- Going a step further than Timmers/Achten, the authors recommended that policymakers should enforce further stringent regulations in the transportation sector regarding emissions as well as promote the usage of alternative means of passenger transport. Such a change would highlight the benefits, both environmental, economic and social of these alternative means (such as human powered and electric two-wheelers).

Conclusion

The ultimate point of the study is captured by the authors in the conclusion:

> *"Policy so far has only focused on reducing PM from exhaust emissions. Therefore, future European legislation should set non-exhaust emission standards for all vehicles and introduce standardized measurement methods. In addition, it is recommended that EV technology such as lightweight car bodies and regenerative brakes be applied to ICEVs, and incentives provided for consumers and car manufacturers to switch to less heavy vehicles."*

The authors noted that "measurements of non-exhaust emissions so far have produced divergent results, depending on the measurement method used. So in order to introduce non-exhaust limits, a standardised measurement method would need to be introduced. Further improvements can be made by encouraging innovation on reducing vehicle weight."

I conclude with a few observations:

- Non-exhaust research is continuing and scientists are learning more and more about non-exhaust emissions, how best to measure and characterize them and their impact on human health.
- Evidence does seem to be mounting that non-exhaust PM is a significant source of emissions that do negatively impact human health. Given the data on PM presented above, I don't expect this is an area that governments will or can continue to ignore for long.
- While there is much research to be done in this area, I expect regulators in the future, perhaps starting with Europe, to tackle the issue of non-exhaust emissions and that could affect both ICEVs and EVs. This is a key future trend to watch for. The question will center on how best to measure these emissions and then set enforceable standards for these vehicles.

- If the authors' analyses are indeed correct, and non-exhaust emissions from EVs is really a serious but unheeded issue until now, does that have the potential to undermine the development of the global EV market? How easy or costly would it be to correct this issue versus correcting it in ICEVs?
- Governments are beginning to mandate EVs and/or set incentives to facilitate their uptake and the auto and other industries are spending billions investing in the technology. Groups like Bloomberg Energy Finance are forecasting a tipping point whereby EVs begin to take off and dominate the fleet within the next 10 years. There seems to be a lot of enthusiasm and public interest in and passion for EVs. However, will the auto industry be caught “flat-footed” down the line when and if PM emissions around the world, especially in big EV markets, worsens because of this non-exhaust issue? Could this be what I call a “sleeping giant” issue?