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Black Carbon Problems in Transportation: Technological Solutions and Governmental Policy Solutions

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Abstract

The adverse effects of black carbon (BC) emissions from diverse sources are significant in human and economic terms. BC emissions are a public health problem, as they annually cause premature deaths on the order of millions worldwide. BC also has detrimental effects on food supplies, with crop production reduced by millions of tonnes per year. In addition, BC has significant climate change consequences, with a Global Warming Potential per tonne on the order of thousands of times greater than carbon dioxide's over a 20-year period; in terms of total global warming impact, BC is second after carbon dioxide and thus greater than other greenhouse gases, including methane. Emissions mitigation technologies and government policies offer potential health, food and climate *co-benefits*. Within the transportation sector, there are many technologies and policies that can mitigate BC emissions; for example, inter-modal transfers of diesel particulate filter (DPF) technology from motor vehicles to maritime shipping offer a promising BC mitigation path. BC not only poses significant tangible technological issues; it also poses important political-economy conceptual issues with practical implications for industry and government policymaking. First, because of its short atmospheric lifetime average of about one week and concentrated localized depositions, BC poses "local-commons" and "regional-commons" problems as well as "global-commons" problems. Second, because of its localized and regionalized multiple negative externalities, BC challenges the economic efficiency rationale for one-policy-instrument-per-goal. The BC policy agenda thus extends over many levels of governance, and it entails a wide range of policy instruments. The multiplicity of policy

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instruments at multiple levels of governance are reflected in the assessment of existing policies and in the diversity of recommendations for further policymaking and research: (1) BC emission measurement deficiencies for motor vehicles and aviation need to be corrected, and a maritime shipping protocol in the International Maritime Organization should be finalized and adopted. (2) In addition to on-road motor vehicles, local BC emission reduction initiatives should be adopted, especially in large cities with seaports and airports. These programs should encompass all diesel engine sources of BC in maritime shipping and aviation port infrastructure areas, including off-road vehicles, loading/unloading equipment, and diesel locomotives. (3) Mitigating BC emissions should be an urgent objective in the International Civil Aviation Organization (ICAO) and International Maritime Organization (IMO). (4) Technology transfer issues, including transfers of diesel particulate filter technologies in motor vehicles and maritime shipping, should be included on the agenda of the Technology Mechanism of the UNFCCC. (5) All maritime shipping Emission Control Areas (ECAs) should include BC emission limits. (6) An Arctic Black Carbon Agreement in the form of a “carbon club” should be developed. (7) Annual COP meetings and other activities of the UNFCCC should expand recognition that BC mitigation can be included in countries’ Nationally Determined Contributions. (8) The prevailing climate change paradigm should be revised.

Key words: Black Carbon; Soot; Carbon Clubs; Paris Agreement.

JEL classification: F13; F18; O38; Q54; Q58.

1. Introduction

The purpose of the paper is to assess: (a) problems resulting from emissions of black carbon in transportation, and (b) technologies and policies that can mitigate such emissions. The analysis includes emissions from maritime shipping as well as motor vehicles and aviation – and their effects on climate change, public health and food production.

A simple definition of black carbon (BC) is that it is carbon particulate matter less than 2.5 microns across ($PM_{2.5}$) resulting from the incomplete combustion of fossil fuels, bio fuels and bio mass. (Black carbon is *not* “carbon black,” which is a manufactured product that is used, for instance, to strengthen and blacken tires.)

A more extensive definition of BC from a landmark study (Bond et al., 2013: 5389) is that it is “ambient aerosol material” which is ...

a distinct type of carbonaceous material, formed only in flames during combustion of carbon-based fuels. It is distinguishable from other forms of carbon and carbon compounds contained in atmospheric aerosol because it has a unique combination of the following physical properties:

1. It strongly absorbs visible light
2. It is refractory; that is, it retains its basic form at very high temperatures
3. It is insoluble in water, in organic solvents including methanol and acetone, and in other components of atmospheric aerosol
4. It exists as an aggregate of small carbon spherules.

BC is commonly called “soot,” though this shorthand expression is not precise because soot contains other elements in addition to BC. In particular, in the context of climate change issues, it is important to distinguish between black carbon and organic carbon, which are both present in soot; whereas black carbon has a warming effect, organic carbon has a cooling effect. Since they are co-pollutants in soot, the relative amounts of black carbon and organic carbon in the emissions of different sources are important. However, because there is a consistently large ratio of black carbon to organic carbon in *diesel engine emissions*, those emissions are widely recognized as a major source of BC and thus a major contributor to global warming (IPPC, 2013: 360-361; Azzara, 2013; 2015; Ramanathan and Carmichael, 2008; Smith et al., 2009: Table 4.9; US EPA, 2017).

Diesel engines’ emissions are therefore a central concern of the paper. Although the paper focuses on maritime shipping, aviation and on-road motor vehicles, much of the analysis also pertains implicitly to off-road vehicles such as in agriculture and construction, as well as diesel locomotives, diesel-powered materials-handling equipment and diesel-powered electric generators.

The remainder of the paper considers the effects and sources of BC emissions in section 2, technologies in section 3, policies in section 4, and concluding implications in section 5.¹

¹ A separate paper in progress - “Political Economy Paradigms of Climate Change Mitigation and Their Policy Implications” – considers the analytic model-building and government policymaking issues posed by black carbon emissions. There is also another topic of considerable policy and theoretical significance that should be explored further, namely that black carbon emissions, as depicted in the present paper, are examples of “*non-uniformly mixed* pollutants, where location matters,” as discussed in Benear and Stavins, (2007: 124). Although an “ambient tradable permit system” would therefore seem in principle be an appropriate policy, its impracticality leads them to the following suggestion: “A market-based Instrument - such as tradable emission permits or an emission tax (in the interest of cost effectiveness) - can be combined with localized ambient standards to prevent concentrations from exceeding accepted levels in particular localities (so-called ‘hot spots’).”

2. Problems

2.1 Effects

The physical and chemical features of BC account for a wide range of effects when it is emitted, namely: (1) health effects including lung cancer and cardiovascular problems, (2) reductions in food production from BC deposits in growing areas, and (3) climate change through BC's warming effects as an aerosol in the atmosphere and as depositions on snow and ice. Each of these three categories of effects exhibits distinctive characteristics, and the profiles of the human and economic costs of the three are also distinctive (Shindell et al. 2012a; 2012b; Anenberg et al., 2011).

The *health* effects of black carbon emissions from a variety of sources are known on the basis of a large number of studies over several decades (WHO, 2012: vii). The health effects include premature deaths from lung cancer and cardiovascular problems, as well as lost work and health care costs from chronic and acute cases of asthma and other disorders. BC's health effects are evident from studies of both short-term (daily) and longer-term variations in exposure levels. Although health studies of the effects of BC have typically been focused as a matter of metric convenience on particulate matter of 10 microns or less across, it is the smaller PM_{2.5} particles and BC in particular that are the principal cause of health problems. BC emissions worldwide cause on the order of millions of premature deaths per year (US EPA, 2012: 21).² About 125,000 annual deaths in the US have been attributed to particulate matter from diesel vehicles (Bahner et al., nd).

Studies of the *food production* consequences of BC emissions have been less extensive, but results to date indicate that BC reduces the yields of many crops. For instance, the crop yield loss from BC emissions worldwide for four crops – maize, rice, soybeans and wheat – have been estimated to be on the order of tens of millions of tonnes per year (UNEP and WHO, 2016).

As for BC's contributions to *climate change*, the cause-effect relationships are more complex; there are both generic metric issues and BC-specific metric issues (US EPA, 2012: 56-66). The generic issues reflect the fact that climate scientists typically measure the cumulative radiative effect of various forcing agents by watts per square meter (W/m⁻²), often covering the period from circa 1750 before the industrial revolution to recent years US EPA, 2012: 32). Although this is a useful metric for determining historically the relative contributions of climate forcers to present temperatures, it is not necessarily useful for *policy* purposes when the principal concern is the *future*. In the context of the present paper - where the focus is on modern modes of transport - the relative contributions in past centuries of motor vehicles, maritime vessels and airplanes are obviously not indicative of their current or prospective contributions. Thus, metrics for Global Warming Potential and Global Temperature Potential are used in the paper, as discussed below.

² Volumes of BC emissions as PM_{2.5} are strongly correlated with volumes of PM₁₀ over time and across areas.

In addition to these generic metric issues, there are BC-specific metric issues about BC's contribution to climate change: analyzing the effects of BC emissions on climate change is challenging because of the presence of organic carbon (OC) emissions as co-pollutants with BC emissions. A key determinant of the *net warming/cooling impact of emissions* is the ratio of BC to OC (IPCC, 2013). The ratio of BC to OC in diesel emissions has been estimated to be as high as 9:1 (Azzara, 2013; 2015). Mobile diesel engines' BC emissions have been specifically estimated to be about 75 percent of soot's total (US EPA, 2017).³

Diesel fuel's high BC/OC ratio is therefore a key factor justifying the treatment of diesel engines as significant net sources of global warming.

The formation of clouds from BC emissions poses additional challenges to the estimation of net warming impacts. It is common practice, therefore, to distinguish between BC's "direct effects," which do not take into account cloud formation, and BC's "indirect effects," which refer to cloud effects. For instance, BC's "direct effects" on arctic surface temperature warming have been estimated to be 0.4°C from BC in the atmosphere and 0.22°C from BC on snow. These estimates, however, do not include "indirect effects" from cloud formation (AMAP, 2015: 96). "Total effects" - or "total net effects" - include both direct and indirect effects.

Despite these measurement challenges, it is nevertheless possible to estimate both the *per unit warming impact* of BC emissions and the *total global warming impact* of all BC emissions in order to establish the relative significance of BC as a global warming agent. *Per unit* comparisons with carbon dioxide are presented in Table 1, where metrics for both Global Warming Potential (GWP) and Global Temperature Potential (GTP) are presented. GWP is the integrated value of the cumulative effects of one pulse of BC at a specific time over the indicated subsequent period of time (usually 20 years or 100 years). GWP thus cumulates the effects over a specified time period, but it does not include emissions after that period of time. GTP indicates the temperature for one selected year with no weight for years before or after the selected year (IPCC, 2013, Technical Summary: 58). GWP is more commonly used in the climate change literature, but there are examples of the use of GTP as well.

Estimates of BC's impacts by the Inter-governmental Panel on Climate Change (IPCC) - which of course have been based on more data and more studies over time through five IPCC cycles of assessing climate science - have generally become larger. The data in Table 1 are based on the most recent IPCC estimates from Assessment Report 5 (IPCC, 2013). The table presents data for both 20-year and 100-year time horizons. Although 100 years has been a widely-used time horizon on the grounds that the average atmospheric lifetime of carbon dioxide is

³ In contrast to the dominance of BC in diesel emissions, OC dominates in biomass burning (US EPA, 2017).

about 100 years,⁴ a horizon of 20 years is often used for short-lived carbon pollutants such as BC. Table 1 also presents four different indicators for BC – from three separate studies, one of which includes the *albedo* effect of BC, which reduces snow and ice reflectivity. The most inclusive indicator, which is in the bottom row, shows an estimate of 2900 for BC's GWP relative to carbon dioxide's at 20 years. Despite issues about particular metrics, the basic patterns in Table 1 are clear: BC's impact *per tonne* is much greater than carbon dioxide's, with an order of magnitude from tens to thousands of times greater.

Table 1: Global warming impact per unit of black carbon emissions compared with carbon dioxide (mean estimate and 95 percent confidence interval)

Sources and scope of emissions data	GWP ^a 20 years	GWP ^a 100 years	GTP ^b 20 years	GTP ^b 100 years
Bond et al. (2013): global	3200 (270-6200)	900 (100-1700)	920 (95-2400)	130 (5-340)
Collins et al. (2013): global	1600	460	470	64
Fuglestvedt et al. (2010): four regions ^c	1200 (+/-720)	345 (+/-207)	420 (+/-190)	56 (+/-25)
Bond et al. (2013): BC global – radiation + albedo	2900 (+/-1500)	830 (+/-440)	NA	NA

^aGWP = Global Warming Potential

^bGTP = Global Temperature Potential

^c Regions: East Asia, European Union + North Africa, North America, South Asia. Includes aerosol-radiation interaction.

Source: Brewer (2015: 3, Table 1); adapted from IPCC (2013: 740, Table 8.A.6).

As for BC's *total* global warming impact, it has been estimated most recently (Bond et al., 2013) to be 55 percent of carbon dioxide's impact, and thus more than any of the other greenhouse gasses, including methane.⁵

⁴ A rarely-noted feature of the distribution over time of carbon dioxide atmospheric lifetime: About 20 percent remains in the atmosphere for *thousands* of years. The commonly-used figure of 100 years underestimates carbon dioxide's impact.

⁵ A recent study of methane emissions (Lavoie et al., 2017) based on aerial measurements estimated that methane emissions from power plants fueled by natural gas could be 21 to 120 times higher than US EPA estimates and that emissions from oil refineries may be 11 to 90 times higher than EPA estimates. It is not yet known how much underestimates are also evident for other sources – and thus the extent to which global estimates should be increased.

A distinctive and significant feature of BC emissions is that their effects are experienced directly at local and regional levels because they result in particulate matter depositions as well as atmospheric pollutants. Thus, in addition to its role as a global climate change forcer, BC is a locally and regionally evident pollutant.

2.2 Transportation sector sources

Measuring and projecting transportation sector emissions of BC are particularly challenging because of the distinctive sets of issues associated with individual industries. For the motor vehicle industry, the most salient issues of course are the manipulations of official emissions testing by automotive manufacturers in the US and Europe, which have led to significant under-reporting of emissions. Conventional aviation measures based on a “smoke number” also underestimate BC emissions. BC measurement methods in maritime shipping are currently undergoing a protocol development process at the International Maritime Organization. More details follow below for each of the three.

On the basis of the available data, the transportation sector in the United States is estimated to account for about 52 percent of US black carbon emissions, and diesel engines contribute about 90 percent of the transportation BC emissions. Globally, transportation accounts for approximately 19 percent of BC emissions, and diesel engines contribute 90 percent of transportation’s share. Whereas BC emissions are reported to be decreasing in the US and Europe (though there are reasons to doubt this, as we shall see below) they are increasing in most of the rest of the world, especially in China and India. Of course, projections of future levels are more policy relevant, and they are presented below.

2.2.1 Motor Vehicles

In the motor vehicle industry, there are continuing questions about the accuracy of the actual levels of BC and other emissions compared with the reported emissions from tests in the US and EU. Though there have been acknowledged underestimates as a result of some firms’ practices, how big the required corrections are for aggregated US and EU estimates is still being investigated.

Emission testing controversies for the motor vehicle industry in the US and in Europe have attracted much attention to emissions standards and testing procedures. While the controversy in the US has been focused on the test-defeating equipment of a particular manufacturer, in the EU the controversy has been more broadly concerned with industry-wide standards and test procedures. The standards adopted by the European Commission under pressure from the industry are higher than originally intended by the Commission; and the tests, which are conducted by firms selected and paid by the auto manufacturing firms not by the Commission or independent third parties, are not subjected to rigorous quality control procedures.

In addition, in Europe at least one of the heavy truck manufacturers has used an unreliable comparison of a single unrepresentative vehicle in one year with a single unrepresentative vehicle from a later year of a different kind from the first vehicle (Muncrief, 2017). The suggestion that therefore vehicle fuel efficiency improved by 30 percent over the 1965-2010 period has been subjected to careful

analysis (Muncrief, 2017), which concluded that a methodologically respectable comparison would yield no significant improvement over the period 2002 to 2014 based on tests of 98 vehicles.

2.2.2 Aviation

As for aviation, there is also evidence of underestimates of BC emissions - not because of deception in testing for emissions levels, but because of the inherent inadequacies of traditional measurement methods. When aviation's BC emissions have been subjected to rigorous analysis in recent years, a key finding is that the commonly-used metric "smoke number" *underestimates* emissions. The smoke number only indirectly estimates the mass of BC emissions by optically measuring the visibility of the plume of an aircraft - during cruise speed as well as take-off and landing. It is not a direct physical chemical measurement.

One study (Stettler et al., 2013a) found that the smoke number underestimates BC emissions by a factor of 2.5 to 3, thus indicating that current estimates of aviation BC need to be increased by a factor of similar magnitude. Another study (Stettler et al., 2013b) found that the estimate of global aviation BC emissions should be about 3 times greater than earlier estimates, or equal to about one-third of the radiative forcing of aviation's carbon dioxide emissions. A study of UK airports representing 95 percent of UK passenger traffic in 2005 (Stettler, Eastham and Barrett, 2011) also found greater BC emissions than those in studies using the smoke number; in fact, more direct alternative measurement methods found BC emissions to be 8 times greater than smoke number studies. The effects of organic carbon (which is a coolant, as noted above) were also found to be higher, but only by a factor of 0.4.

Overall, then, the results indicate that aviation BC's net global warming impact is substantially greater than previously estimated using the traditional optically-obtained smoke number. More consensus and precision about the amount of upward correction that is needed therefore awaits further studies.

In any case, aviation *traffic volumes* are expected to increase for at least the next few decades, as they have for the past several decades, typically by more than the rate of increase in world GDP. Forecasts by ICAO (2016: 10, 23) are that total world passenger traffic will increase by an average of 4.6 percent per year over the 20 year period from 2012 to 2032 and 4.5 percent over the 30 years from 2012 to 2042. These forecasts compare with 5.2 percent per year on average that was experienced from 1995 to 2012. The parallel forecasts for freight traffic are averages of 4.6 percent and 4.5 percent per year.

The two dominant manufacturers of aircraft also make periodic forecasts, with a focus on the numbers of planes. Thus, Airbus (2016) forecasts for the period 2014-2034 a 102 percent increase in the world's total fleet of planes from about 19,000 to about 38,000 – with a 106 percent increase in the passenger aircraft fleet and a 65 percent increase in the much smaller freighter fleet. Boeing's (2016) forecast for the 2015-2035 period is quite similar at 105 percent. In sum, over the next two decades, commercial air traffic can be expected approximately to double.

In sum, the combination of at least a doubling of air traffic volume - with the greater and more accurate estimates of BC emissions per tonne-kilometer - bodes

ill for business-as-usual (BAU) aviation contributions to global warming. Despite improvements in aviation fuel efficiency, BC emissions will increase substantially.

Aviation's BC emissions are not evenly distributed around the world, however. There is a trans-Atlantic concentration just south of Greenland and Iceland – a concentration pattern that contributes to the relative high warming trends in the Arctic region. Otherwise, the emissions are concentrated in North America, especially in the east, as well as Western Europe, Japan and the east coast of China. These patterns thus create regional-level as well as local-level and global-level BC issues.

2.2.3 Maritime Shipping

IMO estimates of BC emissions in the maritime shipping industry have been found to be underestimating actual levels. Wang and Minjares (2012) computed global estimates for 2007 that were 42 percent higher than IMO's estimates, and Arctic region estimates for 2004 that were 90 percent higher than IMO estimates. Insufficient data and modelling about BC emissions and depositions in the Arctic have led to underestimates of role of BC in Arctic sea ice melt and land ice melt in the Arctic region. Recent studies, which have begun to correct for these past deficiencies have been contributing to the increased understand – and increased alarm – about the rate of change in the Arctic region. See especially AMAP (2011; 2015); also see Azzara (2013); Azzara (2015); Azzara and Rutherford (2015); Brewer (2015; 2016); Comer et al. (2017); Corbett, Lack, and Winebrake (2010); Eleftheriadis (2009); Hegg, et al. (2009); International Council on Clean Transport (ICCT) (2015); McConnell et al. (2007); Sharma et al. (2006); and Tedesco et al. (2015). Corbett and Winebrake (2008: 18) found that marine fuel sales statistics have led to underestimates of marine energy use by a factor of two

As for the volumes of vessel traffic and their loads, they have been strongly correlated with GDP at the global and national levels (Corbett and Winebrake, 2008: 7-9). However, the relationship has not been stable over time: As reported in UNCTAD (2016: 5, Box 1.1), "Long-term trade–GDP elasticity was estimated at 1.3 in 1970–1985, 2.2 in 1986–2000, 1.3 in the 2000s and 0.7 in 2008–2013."

Forecasts of future shipping activity and thus emissions should of course be interpreted cautiously. In any case, maritime shipping's BC emissions have been forecast to approximately triple by 2050 versus 2004, despite IMO fuel efficiency regulations (Corbett, Lack, and Winebrake, 2010; Azzara, Minjares and Rutherford, 2015).

Overall, then the futures of these three transportation industries offer the prospect of significantly increasing BC emissions – unless there are technological and/or policy changes. Beyond this basic similarity in their outlooks, however, there are significant differences among them in the technological and policy issues they face.

3. Technological Solutions

3.1 Motor Vehicles

Diesel particulate filters have been used on motor vehicles for decades, and they have been found to be cost-effective (MECA, 2007). The black carbon emissions issues are, therefore, more about the installation, standards, testing, monitoring and enforcement *policies* – which are discussed in section 4 below.

3.2 Aviation

Because aviation fuel has a different emission profile compared with the diesel fuel used in motor vehicles and ships, the technological issues for reducing black carbon emissions are also different. Yet, there are also some fundamental similarities in the search for fuel efficiency and for alternative fuels. In the case of aviation, however, there are special challenges and opportunities (Hawken, 2017: 150-151). There are many opportunities for improved fuel efficiency, in both aircraft design and operations: Winglets can improve fuel efficiency by 5-7 percent depending on their precise design, but their uptake has varied among airlines (some planes of some airlines still do not have them). More opportunities exist in “placement of engines, fuselage width, width, length, and placement of wings” As for alternative fuels: “Jet biofuel options exist today, but cost is high, supply is limited, and infrastructure is poor.”

What about future uptakes and emission levels? Air Transport Action Group (2015) lists 100 possibilities in a broad range of possibilities – including efficiency in the air, efficiency on the ground, building and construction, and many more. A US National Academies of Sciences (2015) Committee focused on propulsion and energy technologies with a 30-year horizon and an emphasis on carbon dioxide emissions. Most of their recommendations require large, long-term investments in R&D, with highly uncertain payoffs. One specific possibility, however, might offer shorter term and less capital, namely improvements in gas turbine engines “with a potential to reach overall efficiencies perhaps 30 percent higher than the best engines in service today” (Air Transport Action Group, 2015: 6).

The MIT Joint Program on Science and Policy conducted an extensive modeling exercise of future global aviation emissions, including BC emissions. They found BC levels of emissions in 2050 that were 1.38 to 4.87 times greater than 2006 levels (Brasseur, et al., 2016: 567, Table 2).

In sum, there are numerous and diverse technological alternatives that could eventually increase fuel efficiencies. Whether they would be enough to offset increases in traffic volume and whether the rate of uptake would be sufficient would of course depend on

3.3 Maritime shipping

In maritime shipping, the potential black carbon emissions reductions from particulate filters and other mitigation technologies, as well as operational

procedures, have been reported in two studies. A review of the literature found that particulate filters could reduce black carbon emissions by 80 percent to 90 percent (see Table 2).

Table 2. Maritime Shipping BC Reduction Technologies

Emission Reduction Technology	Expected Emissions Reduction (%)	
	Low	High
Diesel Particulate filters	80	90
LNG	50	90
Fuel switching (LSF)	30	80
Exhaust gas scrubbers	20	70
Water in fuel emulsion	45	50
Slide valves	25	50
Exhaust gas recirculation	0	20

Another study by Litehauz and others for the IMO (2012) compared several black carbon abatement technologies in terms of a variety of criteria, including cost-effectiveness as well as the percentage of black carbon reductions. An 85 percent reduction for diesel particulate filters was precisely in the middle of the range in the table above from a separate study. A comparison of DPFs with switching-to-LNG-fuel revealed the complexities and tradeoffs of comparing abatement technologies; for instance, although LNG was higher in cost-effectiveness in general, the lack of bunkering fuel infrastructure is a barrier to its adoption.

A review by an industry organization, The International Council on Combustion Engines which is also known by its French name and acronym CIMAC (2012), included comparisons of black carbon emissions abatement technologies for “large marine and stationary diesel engines.” It concluded that DPFs were “not viable systems for large diesel engines operating on non-automotive fuel qualities” – i.e. large ships (CIMAC, 2012: 22). This raises the possibility that DPF technology could be transferred from motor vehicles to small and medium sized vessels, at least initially, and then perhaps later adapted for large vessels (see ICCT, 2016a, for additional information about this possibility).

4. Government Policy Solutions

It is easy to imagine a simple 3x3x4 cube representing 36 policy spaces defined by the combinations of three sectoral *sources* of BC emissions, their *effects* on health, food and climate, and four *governance levels* – local, national, regional and global.

Within each policy space there is a distinctive cluster of issues. But the clusters also have some common elements; for instance, the common use of diesel engines in both motor vehicles and maritime shipping vessels was highlighted above.

Although it is not feasible here to discuss each of the 36 clusters, it is possible to illustrate their diversity and to highlight currently salient issues in reference to each of the three transportation sectors. Although there are on-going policy developments in many parts of the world, the ones here are largely drawn from Europe because there is more policymaking activity there than in other areas. In the US of course, there is much uncertainty in light of the changes underway or proposed by the current administration – and because the future of the administration itself is also unusually uncertain. As for China, there is certainly increasing interest and activity on the problem of air quality, including BC issues in major cities and ports.

Some of the measures reported below are specifically intended to reduce diesel emissions and thus BC emissions; others are focused on carbon dioxide, but with effects on BC emissions as well.

4.1 Motor Vehicles

The EU is considering reforms of motor vehicle emissions standards and testing procedures in response to deficiencies in the current system (Transport & Environment, 2017). The second largest auto manufacturer in Europe - PSA, which makes Peugeots, Citroens, Opels and other brands - publishes *on-road* fuel consumption data for 58 models of cars. Compared with officially-sanctioned lab tests conducted by organizations contracted by the auto manufacturers, the *on-road* tests reveal 42 percent and 45 percent higher levels, respectively, for Peugeots and Citroens, compared with the officially-sanctioned lab tests.

Heavy duty truck manufacturers, in particular, have been on the defensive on two policy fronts. One concerns the use of methodologically flawed reports of purported improved fuel efficiency – 30 percent over 1965-2010 and 60 percent over 19675-2014, compared with the results of a more methodologically robust study (Muncrief, 2017) covering 2002-2014 trucks by six major European manufacturers, which found no significant change. Developments on the other policy front concern compliance with EU competition policy law. The largest competition policy fine in EU history - 2.93 billion euros, or about 3.28 billion US dollars – was imposed on the basis of five firms colluding in a cartel over 14 years, including “coordination on timing and coordination on passing on of costs of emission technologies for trucks compliant with newly introduced emissions standards” (European Commission, 2016). The firms were MAN, Volvo/Renault, Daimler, Iveco, and DAF, though MAN did not have to pay a fine because it revealed the cartel to the Commission.

Partly in response to revelations of inadequate test procedures – known as ‘dieselgate’ - and partly as a result of increasing awareness of air quality and associated health problems, many European cities have begun to limit diesel

vehicles.⁶ The cities of Athens, Madrid, and Paris plan to ban diesel cars and delivery vans by 2025, and other cities are considering such measures. Barcelona, Berlin, Cologne, Munich and Stuttgart are putting in place restrictions or considering them. By March 2017 new diesel car registrations were at 5-year lows in France, Germany, Spain and the UK (Tietge and Diaz, 2017).

Norway has established a national target of eliminating all new fossil-fuel cars by 2025; current policies include tax incentives, preferred access to municipal parking facilities, and waivers of fees for ferries and toll roads. As of the first two months of 2017 in Norway, there were more new EVs and hybrid cars purchased than new fossil fuel cars (Forrest, 2017).

Mexico City has also decided to ban diesel vehicles, and it has included the reductions of black carbon emissions in its Paris Agreement list of Nationally Determined Contributions.

4.2 Aviation

Air quality policies concerning aviation are of course fundamentally different from those for motor vehicles or maritime shipping: diesel engines are not a factor in aviation, except for ground services and equipment. Nevertheless, as noted above in section 2, there are significant black carbon emissions from aircraft, and traditional measurement methods underestimate the volume of black carbon emissions from aviation fuel.

Multiple types of policies affecting aviation are at issue at multiple levels of government. Many kinds of policies can limit BC emissions: limitations on the number of flights, changes in air routing and traffic control, increases in fuel efficiency, adoption of alternative fuels, and more. Initiatives to reduce carbon emissions from the aviation industry have been especially numerous in Europe. The initiatives implicitly include BC, though they tend to focus explicitly on carbon dioxide. Policies have been evolving at both the regional EU level and at the national level, with local level issues and impacts in all cases. There are many evolving cases in which the specific issue is whether there will be restrictions - including perhaps prohibitions - of airport expansions, including the addition of runways.

London's Heathrow airport is the best known case, with the plans for its expansion still unresolved. The national UK government made a preliminary decision in October 2016 to approve a third runway, after many years of considering it. However, there are unresolved issues that could delay or prevent the final approval. One is that there are objections to deficiencies in the limitations on carbon emissions of flights using the new runway. The government's response thus far has been to plan emission offset requirements and peat bog restorations in compensation. Second, because of the projected increase in emissions at Heathrow, there may be a need to reduce emissions in other sectors in order for the UK to meet its COP21 Paris agreement targets. Finally, there is an issue of whether other

London area airports would have limitations on planned expansions and emissions. Final plans and conditions for the Heathrow expansion are thus pending.

Airport expansion plans in other countries are also in doubt. In Austria a national court has ruled that the planned expansion of the Vienna airport cannot proceed because it would violate Austria's emission targets, but the decision is being appealed. Plans and potential court cases are not so advanced in other countries; however, there are doubts about the fates in Germany for airport expansions at Dusseldorf and Munich, in Ireland for Dublin, and in France for Nantes.

At the regional level, EU policy reflects the basic distinction between intra-EU flights versus flights that are entering the EU from non-EU countries or departing to non-EU countries. Flights involving non-EU countries account for about three times the volume of emissions from intra-EU flights.⁷ The current EU policy is to include only intra-EU flights in the European Emission Trading System (ETS). Extra-EU flights have been excluded from the ETS, at least until an agreed International Civil Aviation Organisation (ICAO) system enters into operation in 2021.

The ICAO system – known as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) - will be voluntary initially and not become mandatory until 2028 (ICAO, 2016; ICCT, 2017). Even then, the ICAO system will not reduce the industries' emissions below business-as-usual projections (Rutherford, 2016). Whether the EU will include extra-EU flights in the ETS at some point during the 2021-2028 period, or after, obviously remains to be seen. In any case, CORSIA does not explicitly include black carbon emissions; in fact, black carbon emissions have not explicitly been on the ICAO agenda. Yet, in 2004, ICAO adopted a goal that is potentially relevant to black carbon emission reductions – i.e. to “limit or reduce the impact of aviation emissions on local air quality” (ICAO, 2017; also see Romera and van Asselt, 2015 for a review of developments in ICAO on emission regulations).

4.3 Shipping

As with aviation, there are developments concerning shipping's emissions at many levels of government. The targeted emissions in some cases include diesel emissions and thus black carbon. In other cases, the explicit target is increased fuel efficiency that would reduce emissions, including black carbon emissions. A limitation of fuel efficiency measures of course is that the increases in efficiency must more than offset increases in volumes of traffic. This is especially a problem in maritime shipping, as it is in aviation.

⁷ Because emissions from *domestic* aviation are included the UNFCCC, parties to the UNFCCC can reduce emissions from these sources in the context of their Nationally Determined Contributions (NDCs) under the Paris Agreement.

At the local level, in North America four Pacific coast cities - Los Angeles, Long Beach, Oakland and Vancouver - have all adopted policies that reduce BC emissions. Los Angeles and Long Beach together reduced particulate matter emissions, including black carbon, by 81 percent as of 2013 compared with 2005. An interesting feature of their program is to use *positive incentives in the form of cash payments for each vessel entering the ports that meets voluntary emission standards* – as opposed to negative penalties for non-compliance with mandatory limits.

In Europe, Gothenburg and Rotterdam are in the process of implementing regulations on ships in their ports. At the regional EU level, the situation is more complex. There is support in the Commission and in the Parliament to put the International Maritime Organization (IMO) on notice that the EU will include shipping in its Emission Trading System starting in 2023, unless the IMO agrees to a global system that would reduce shipping's emissions. The EU proposal is pending approval by its national member governments, who are divided.

In Asia, the most important policy issues concern the major long-term sea port expansion plans in India and China. India has plans to develop ten new mega-ports and upgrade 12 existing government-owned ports; in addition, private developers have plans to create several new private ports (Mundy, 2017). As for China, about two-thirds of the world's 50 largest container ports are wholly-owned or partly-owned by Chinese investors (Kynge et al., 2017). Its Maritime Silk Road plan includes about six ports in China and another 15 or so in other countries, including 7 in Africa and 4 in Europe. Some have already been built, others are in advanced construction stages, yet others are in planning (Kynge, 2017). Given the numbers and sizes of these Indian and Chinese projects, emission control policies at their facilities will affect regional and even global BC emission levels, as well as local emissions of course. Chinese Maritime Silk Road port projects in foreign countries will be subject to local policies, of course. In Europe this would mean, for instance, being subject to relatively strict policies in Rotterdam, Netherlands, and Hamburg, Germany, and perhaps Athens and Venice as well, since Greece and Italy are both subject to EU policies.

International regional Emission Control Areas (ECAs) have been established in North American waters and Northern European waters, and national Chinese Emission Control Zones (ECZs) are under development in China (ICCT, 2016b). The North American ECAs have been estimated to prevent a tripling of PM_{2.5} by 2030, mostly through fuel-switching (US EPA, 2010).

There is a proposal for a regional agreement for the Arctic that is specifically focused on black carbon (Brewer, 2015; 2016). It could be modelled in some respects on the existing ECAs, or perhaps even attached to one of them as an extension.

In terms of global scale regulation in maritime shipping, the International Maritime Organization (IMO) is the designated international institution, as a UN Specialized Agency in general for international maritime issues and as designated by the UNFCCC process to be the climate change agency for international maritime shipping. (Domestic shipping remains the province of national governments.) The most relevant IMO activities concerning black carbon emissions have followed two tracks. One is the fuel efficiency track, which has promulgated

mandatory regulations concerning vessel design and operations, with different phase-in periods for new and existing vessels (IMO, 2017). The other focuses on black carbon emissions; thus far, it has accepted the definition in Bond et al. (2013), as mentioned in the introduction of the present paper. It has also begun a process of developing a protocol for measuring black carbon emissions (IMO, 2012).

5. Implications

5.1 Industry Patterns

There are both similarities and differences across the three transportation industries in the study in terms of the problems that they face and the solutions that are available. The negative externalities associated with all of the industries' black carbon emissions in their public health, food production and climate change impacts are significant, though the profiles differ across the industries and the types of impacts.

In order to achieve more comprehensive and more precise indications of BC's social costs, it is necessary to have better emissions data. All three industries face significant black carbon measurement deficiencies in determining the levels of emissions, and they have led to underestimates of emission levels. In the motor vehicle industry, in Europe and North America, the significant gaps between emission levels reported from lab tests versus actual on-road emissions have of course been revealed in testing scandals. In other regions, an absence of standards and/or inadequate enforcement of them have led to high rates of undetected BC emissions. In the aviation industry, the conventional optical measurement technique to determine BC levels in airplanes' emissions has been found to underestimate the levels by substantial amounts, compared with more advanced measurement techniques. In marine shipping, agreed measurement procedures have been delayed by a multi-year process of defining BC at the International Maritime Organization (IMO), which is now in the process of a multi-year exercise to develop measurement protocols. In the meantime, there is evidence of underestimates of emissions in widely used data.

There is a common pattern in the geographic scope of the impact of the industries' BC emissions – namely, that they are a combination of local, national, regional and global. The public health effects are localized, and they tend to be especially strong in large, densely populated urban areas with high volumes of motor vehicle, shipping and aviation traffic. Food production effects are more regionalized, including in coastal areas. The climate change impacts are more nearly globalized, though concentrated more in the northern hemisphere than southern hemisphere, and especially significant in the Arctic region (albeit with global consequences).

There are also significant differences among the three industries in the sources of their black carbon emissions and in the technologies and policies that can be applied to them. One key difference is that diesel engines are the primary source of BC emissions in motor vehicles and in maritime shipping – but not a source in aviation. As for technological solutions, diesel particulate filters (DPFs)

have been widely used in the motor vehicle industry for decades and found to be cost-effective, including in their reduction of pre-mature deaths and other health problems. In maritime shipping, although there is on-going research into the potential of DPFs to reduce BC emissions, there is not yet a significant uptake of that technology.

As for alternative fuels, there are significant differences among the three industries. For instance, liquefied natural gas (LNG) has already been utilized in some instances in maritime shipping, especially for ferries, and it could become more widespread for large LNG transport vessels, which can use a portion of their cargo for their own propulsion. There has also been some uptake of liquefied gasses in motor vehicles, busses in particular. In aviation, there has been interest and some experimentation with bio-fuels, but with mixed results and doubts about the feasibility and cost-effectiveness of large-scale use of aviation bio-fuel.

The institutionalized policy regimes concerning BC emissions among the three industries are also substantially different. Motor vehicle emission regulations are overwhelmingly national (in combination with regional rules in the European Union), and they are thus highly variable internationally. Maritime shipping emission regulations, in contrast, have been developed at the global level within the IMO – and to some extent regional level by small groups of countries. The international rules, however, are enforced at the local level by individual ports - some of them under the guidance of national authorities, depending on the nature of the national political system and legal relations among national, local and regional authorities.

5.2 Priority Challenges

These summary findings about industry patterns of the emissions and their effects, as well as the central technology and policy challenges they pose, lead to a broad range of recommendations. Table 3 presents cryptic statements of the central technological and policy challenges in each of the three transportation sectors. The technological challenges vary from developing efficient electric vehicle mass production processes, to adapting diesel particulate filters for shipping vessels, to developing alternative aviation fuels. The policy challenges range from developing mostly national vehicle emissions standards and testing procedures that will achieve significant reductions in the negative health consequences of diesel vehicles of all types, and developing local emissions regulations for motor vehicles, ships and airplanes. At the international level, both the maritime shipping and the aviation industries and their international agencies, ICAO and IMO, face the daunting challenge of developing cost-effective international regulatory frameworks to reduce BC emissions in industries where they are forecast to increase significantly for many years in the future.

Table 3. Central Technology and Policy Challenges

Industry	Technology	Policy
Motor vehicles	Mass producing price-competitive electric vehicles, with a sustainable electric infrastructure	Establishing effective and transparent emissions standards, testing procedures and enforcement mechanisms
Maritime Shipping	Adapting diesel particulate filters and/or LNG technologies to shipping	Establishing coherent local, regional and global BC regulatory framework(s)
Aviation	Developing sustainable alternative fuel(s)	Addressing BC issues in relation to multilateral carbon offset system

Beyond these core challenges, there is a long list of activities needing attention:

- BC emission measurement deficiencies for motor vehicles, aviation and maritime shipping need to be corrected, and the maritime shipping protocol being developed at the IMO should be expeditiously finalized and adopted.
- Local BC emission reduction strategies should be adopted, especially in large cities with seaports and airports. These programs should encompass all diesel engine sources of BC in shipping and aviation port infrastructure areas, including off-road vehicles, loading/unloading equipment, and diesel locomotives as well as on-road motor vehicles.
- Mitigating BC emissions should become an urgent objective in the International Civil Aviation Organization and International Maritime Organization.
- Technology transfer issues, including transfers of diesel particulate filter technologies in motor vehicles and shipping, should be included on the agenda of the Technology Mechanism of the UNFCCC.
- All maritime shipping Emission Control Areas (ECAs) should include BC emission limits.
- An Arctic Black Carbon Agreement in the form of a “carbon club” should be negotiated.
- Annual COP meetings and other activities of the UNFCCC should expand recognition that BC mitigation can be included in countries’ Nationally Determined Contributions.
- The prevailing political-economy paradigm of climate change issues should be revised to reflect: the short atmospheric life span of BC emissions; the potential of co-benefits for health, food and climate from multiple policy instruments; the local and regional patterns of emissions and their depositions; and the multiple levels of governance – local, regional, global – prompted by the existence of “local commons” problems and “regional commons” problems as well as “global commons” problems. The paradigm revision exercise should include evidence of the “social cost” of black carbon.

Such a wide-ranging agenda should involve the participation of industries, governments, non-governmental organizations, international agencies and of course scholars. The payoff for the efforts, however, could be cost-effective measures that could save millions of lives within a few years and many millions more within decades from a combination of their public health, food production and climate change benefits. Thus, a multi-technology, multi-policy, multi-governance-level approach that captures multiple benefits should be pursued.

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