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Russia's black carbon emissions: focus on diesel sources" by N. Kholod et al.

Authors' response

Authors' comments on Review #1

Minor revisions

Comment 1. The health information on p. 1 should be updated to reflect the most recently available health impact information (GBD 2013 was published in early 2016).

Thank you for the suggestion. We updated the text as follows (Lines 36-37 of the updated text):

"According to the Global Burden of Disease study, ambient PM pollution caused over 100,000 premature deaths in Russia in 2013 (GBD, 2016)."

GBD: The global burden of disease study 2013, Institute for Health Metrics and Evaluation, Seattle, WA. Available at http://ghdx.healthdata.org/gbd-data-tool (Last access: 12 July), 2016.

Comment 2. On p. 4, the authors discuss the movement to low sulfur fuel, but omit an important piece of information – low sulfur fuel is necessary for operation of the most effective emission control devices on diesel vehicles. This would be additional context that would be helpful to add.

Thank you. We updated the text as follows (L 121--124):

"Sulfur content of diesel fuel is an important factor in emission reductions. Diesel with high sulfur content (measured in parts per million or ppm) can destroy emission control devices, such as particulate filters. Availability of low sulfur diesel is an important prerequisite for the introduction of more stringent vehicle emission standards."

Comment 3. If the information is available, it would be informative to include the share of industry that is made up of small businesses rather than the number of people employed to give a better indication of the impact of the lack of reporting. (p. 5, lines 149).

Thank you for pointing this out.

Small businesses are not required to submit this information, yet they employ 11 million people (Fedstat, 2015f, a, b, e) **and produced more than 20% of goods and services (GKS, 2015a).**

GKS: Russian Statistical Yearbook 2015. Federal Statistics Service of the Russian Federation. Available at http://www.gks.ru/free_doc/doc_2015/year/year15.rar (last access: 26 February 2016), 2015a.

Comment 4. Authors should consider defining "fuel balance approach" at first mention rather than later in discussion in case readers are not familiar with this methodology. (p. 5, line 155)

We added to the text (Lines: 163-164):

However, their assessments both have their limitations because they do not use a fuel balance approach; *in other words they do not match diesel consumption by on-road vehicles and off-road engines with the production of diesel fuel in the country.*

Comment 5. It is not clear why there is discussion of gasoline vehicles in the section of distribution by emission standards. The authors note that they produce almost no BC, so could easily be left out or addressed with a sentence explaining that they produce almost no BC. If there is a reason the comparison of emission standards is important to the discussion, this should be clarified. (p. 6, lines 198-208)

Thank you for this suggestion. We deleted the discussion about gasoline vehicles. The updated text (L 224-226):

"Figure 2 shows the distribution of diesel vehicles by emission standard. Because gasoline vehicles emit practically no BC, gasoline vehicles were differentiated from diesel vehicles in the on-road fleet and not analyzed in this study."

Comment 6. For logical flow, authors should consider moving the active vehicles section (p. 7, lines 210-221) to immediately following the registered fleet section.

Thank you, we moved the *Active Vehicle* section after the *Registered Fleet* section. (For easy reading, the changes were not tracked).

Comment 7. The assumptions for speed and type of road traveled would benefit from further explanation (i.e., are these based on standard speeds/distribution of roads in Russia?) (p. 9, line 285)

The assumption on the speed in cities is based on actual speed in Moscow and other large cities. The assumptions on the average speed on rural roads and highways are based on maximum allowable (standard) speed on these types of roads in Russia.

The updated text (L 295-299):

"The assumption on the speed in cities is based on actual speed in Moscow and other large cities. The assumptions on the average speed on rural roads and highways are based on maximum allowable (standard) speed on these types of roads in Russia. The share of vehicle-kilometers traveled (vkt) on urban roads is taken from the ICCT Roadmap model (ICCT, 2015)..

The share of vkt on urban roads is 75% for cars, light commercial vehicles, and buses and 50% for trucks. The rest of VKT is divided by 40:60 between rural roads and highways."

Comment 8. The assumptions for controls on agricultural vehicles would benefit from further explanation (i.e., who no Stage 1?) (p. 11, line 351)

We assume that 95% of agricultural fleet has no emission controls and 5% meets Stage 2 standards. Only imported used tractors may have emission controls. In the European Union, Stage 1 emission standard was implemented in 1999 and Stage 2 implemented from 2001 to 2004. Stage 1 tractors might be too old for importing them to Russia so we assume that all imported tractors with emission controls meet Stage 2 standard. Stage 3 standards were phased in from 2006 to 2013, and these tractors are too new to be sold as used in 2014.

We updated the text as follow (L 363-364):

"Tractors imported from Western countries were assumed to have emission controls; however, their share in the total agricultural fleet is very small (no more than 5 %).

Comment 9. For logical flow, recommend moving the paragraph on uncertainty regarding BC/PM ratios after the paragraph on activity data (p. 14). It appears that the BC/PM ratios are NOT a major source of uncertainty, so it would make more sense for the reader if this is discussed after the two major sources of uncertainty that are identified.

Thank you for the suggestion. We moved the paragraph (L 495-498).

Thank you for the useful comments and suggestions!

Authors' comments on Review #2

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"Russia's black carbon emissions: focus on diesel sources" by N. Kholod et al.

We thank the referee for the helpful comments.

Comment 1: Lines 181-184: authors claim "Russia does not have large-scale production of diesel passenger cars", but also say 98% of diesel cars were either imported or produced in Russia by foreign companies. Not sure how this affects the overall emissions, but what fraction of on-road diesel cars are made in Russia by Russian or non-Russian companies? (Also, since this paper focuses on diesel cars, the line about "foreign-make cars, both gasoline and diesel" is superfluous.)

Answer: The Russian vehicle registry shows the following data about registered cars: vehicle type, manufacturer, year of manufacturing, fuel type, emission (Euro) class, and ownership type. The registry data do not allow for distinguishing between imported vehicles and those produced in Russia by foreign companies.

Changes to the text:
We have deleted the phrase "Russia does not have large-scale production of diesel passenger cars" to avoid confusion.

Thank you for pointing out that the line about "foreign-make cars, both gasoline and diesel" is superfluous. We have deleted the line.

Comment 2: Lines 203-204: what higher emissions standards do imported diesel vehicles meet? Euro 6? Or were imported vehicles always produced to meet a higher standard than necessary for Russia?

Answer: Russian mainly imports diesel vehicles from Japan, the European Union, and the United States, with a smaller number of vehicles from South Korea and China. The imported vehicles might meet the emissions standards of the manufacturing countries. Russia adopted European emissions standards about 10 years after the EU, Japan, and the US. As a result, vehicles produced abroad and imported to Russia might meet higher emission standards. However, there is a chance that vehicles produced in foreign countries for the Russian market can only meet the Russian standards. Imported USED vehicles do meet higher emissions standards than necessary in Russia. For example, the EU implemented the Euro 5 standard in 2005 and Euro 6 in 2014 while Russia implemented the Euro 5 standard only in 2016. Among all imported used cars to Russia in 2015, over 70% were vehicles made by Toyota, Nissan, Volkswagen, and Renault.

As a result, when analyzing the distribution by emission standard we rely on the data from the registry.

Correction to the text:
We have deleted this paragraph per comment from the first reviewer.

Comment 3: Lines 240-251: The authors rely on the Bond et al. (2004) assumption of super-emitter fraction as 10%, even though they cite several more recent studies that show superemitters can be as high as 13-15% of the fleet, even in California. Given the lack of studies in Russia, and the authors' literature survey of the Russian fleet (36% of trucks and 23% of buses older than 20 years), using the old Bond et al. (2004) assumption will likely bias their emissions inventory low as the authors acknowledge at the end. The authors should investigate the sensitivity of their results to this fraction, and perhaps try higher values (15-30%) for the super-emitter fraction.

Answer:
We have modified the text to assume that the share of superemitters is 15%. In the sensitivity analysis, we assume that the share of superemitters in the diesel fleet ranges between 10% and 20%.

Changes to the text: please see answer to Comment 7.

Comment 4: Lines 286-287: What is the basis for their assumption of 40-20-40 on urban roads, rural roads, and highways?

Answer:
Thank you for pointing this out. The first reviewer also asked the same question. We updated our assumptions on the distribution of vehicle-kilometers traveled on urban roads, rural roads, and highways. The share of vehicle-kilometers traveled on urban roads is taken from the ICCT Roadmap model (http://www.theicct.org/global-transportation-roadmap-model), and the rest is divided by 40:60 between rural roads and highways (our assumption based on expert judgement).

Changes to the text (L295-299):
"The share of vehicle-kilometers traveled (vkt) on urban roads is taken from the ICCT Roadmap model. The share of vkt on urban roads is 75% for cars, light commercial vehicles, and buses and 50% for trucks. The rest of VKT the rest is divided by 40:60 between rural roads and highways."

Comment 5: The authors use NIIAT data for on-road emission factors, but the actual source of that data is not clear – are these based on measurements or on estimates based on emissions standards? The authors present the data used; a brief explanation of the source methodology will be helpful, since these NIIAT publications do not appear to be easily accessible online.

Answer:
The NIIAT data on emission factors for Russian models are based on measurement. NIIAT has been working on emission methodologies since the 1980s, and tests for vehicles without emission controls (Euro 0), Euro 1 , and Euro 2 were conducted together with the Environmental Department of the Scientific and Research Vehicle Testing Center located in the Moscow region (Donchenko, V., Kunin, Y., Ruzski, A., Vizhenski, V., 2014. Evaluation of road transport effect on atmospheric air: method of emission computations and use of results. Transport Research Arena, Paris. Available at
http://tra2014.traconference.eu/papers/pdfs/TRA2014_Fpaper_19875.pdf).
For foreign models, NIIAT uses emission factors from the European EMEP/CORINAIR guidebook. For its emission calculation methodologies, NIIAT blended emission factors for Russian and European vehicles to reflect the composition of the Russian on-road fleet.

The NIIAT methodologies are not available in English. We worked directly with NIIAT experts and received methodological explanations during multiple meetings. We also presented the results of our emission calculations at a meeting in the NIIAT office in Moscow.

Changes to the text (L 89-92):
"Based on vehicle driving tests conducted with Scientific and Research Vehicle Testing Center, NIIAT has developed emission factors for Russian models. For foreign-made vehicles, NIIAT relies on data from the European EMEP/CORINAIR guidebook. Thus, Russian-specific emission factors for $PM_{2.5}$ in the NIIAT methodologies are based on the average for every vehicle type and emission class on Russian roads."

Comment 6: The conclusions should note that the results exclude military diesel usage emissions; in particular, these could be large sources of sulfate PM, and possibly also BC.

Answer: we updated the text in conclusion as follows (L 542-543):
"These results do not include emissions from military diesel usage. Military vehicles can be a large source of BC emissions given that they use high-sulfur diesel."

Comment 7: While the authors present a comprehensive list of potential uncertainties with their emissions inventory estimate, they don't propagate the uncertainties through, which would be helpful. From their list, it appears the emission factors could produce uncertainties of +/-30% or so, while the bias due to low super-emitter fraction (10% when 15-20% might be more appropriate) could increase the overall BC estimate by as much as 40%!

Answer: For sensitivity analysis we assume that the share of superemitters in the total diesel fleet is in the range of 10%-20% with the central estimate of 15%. We also propagated the uncertainties for on-road vehicles and off-road diesel sources.

Changes to the text (514-524):
"For on-road vehicles, three major sources of uncertainty were considered: the share of superemitters in the fleet, average annual distance traveled, and emissions factors for normal vehicles and superemitters. Supplement Table S10 shows the assumption for uncertainty calculations for on-road vehicles.

The central value of BC emissions from on-road vehicles in 2014 is 20.7 Gg with an uncertainty range of -10.2 Gg and + 7.3 Gg. The central value of OC emissions is 10.5 Gg with an uncertainty range of -4.2 Gg and + 3.2 Gg.

Supplement Table S10. Uncertainty estimates for BC and OC emissions from on-road vehicles

	Central	Minimum	Maximum
Share of superemitters	15%	10%	20%
Annual distance traveled, km	Avtostat	NIIAT	Avtostat
Cars	15 000	15 000	15 000
LCVs	55 000	30 000	55 000
Trucks	63 000	45 000	63 000
Buses	65 000	50 000	65 000
PM emissions factor	COPERT	COPERT -20%	COPERT +20%
BC/PM speciation ratio	COPERT	COPERT -10%	COPERT +10%
Emissions, Gg			
BC normal	11.8	7.1	12.3
BC superemitters	8.9	3.4	15.7
BC total	**20.7**	**10.5**	**28.0**
OC normal	5.6	4.3	5.0
OC superemitters	4.9	2.1	8.7
OC total	**10.5**	**6.4**	**13.7**

The uncertainty in BC emissions from off-road sources is estimated in the range from 19.2 Gg to 42.1 Gg (or -33%/+48%) with the central value of 28.5 Gg. OC emissions from off-road engines are in the range from 4.5 Gg to 9.8 Gg with the central value of 6.7 Gg.

The total emissions from diesel sources in Russia are estimated to be 49.2 Gg of BC and 17.2 Gg of OC in 2014."

Comment 8: One final concern is that the current submission has no explanation of differences between this paper, and the on-road BC emissions estimate published earlier by the first author

(Kholod and Evans, http://dx.doi.org/10.1016/j.envsci.2015.10.017) While the current paper is more detailed, the bottom line figure appears the same - in 2015, Figure 1 of Kholod and Evans shows 20,000 tons of BC from on-road Russian sources similar to the current paper. Maybe the complicated model of the current submission is not needed?!

Answer:
There several important differences between this article and Kholod and Evans (2016).

- Kholod and Evans (2016) use the Global Change Assessment Model (GCAM) to build a forecast for BC emissions from on-road transport (Figure 1). The model calculates emissions in 5-year time intervals. Though the model is a powerful tool to project BC emissions, the model does not distinguish between diesel and gasoline vehicles and does not show the BC distribution by emission standards.
- The current study uses activity-based emissions factors (g/kg fuel). As we show in the article, large uncertainty exists in the fuel consumption by on-road vehicles (in the range from 11 million tons to 22 million tons). In the current study, the emission calculations for on-road vehicles do not use fuel data. Instead we use data on annual distance traveled and activity-based emission factors (g/km). This approach allows us to calculate emissions by vehicle type and emission standard. We also account for superemitters.

Changes to the text (L470-473):
"Similarly, Kholod and Evans (2016) use the Global Change Assessment Model (GCAM) to build a forecast for BC emissions from on-road transport in Russia. Total BC emissions from on-road transport were estimated to be about 20.0 Gg in 2015. The model, however, does not calculate emissions from vehicles by emission standard, which is important for developing emission reduction strategies."

Russia's black carbon emissions: focus on diesel sources

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Abstract. Black carbon (BC) is a significant climate forcer with a particularly pronounced forcing effect in polar regions such as the Russian Arctic. Diesel combustion is a major global source of BC emissions, accounting for 25–30 % of all BC emissions. While the demand for diesel is growing in Russia, the country's diesel emissions are poorly understood. This paper presents a detailed inventory of Russian BC emissions from diesel sources. Drawing on a complete Russian vehicle registry with detailed information about vehicle types and emission standards, this paper analyzes BC emissions from diesel on-road vehicles. We use the COPERT emission model with Russia-specific emission factors for all types of on-road vehicles. On-road diesel vehicles emitted 21 Gg of BC in 2014: heavy-duty trucks account for 60 % of the on-road BC emissions, while cars represent only 5 % (light commercial vehicles and buses account for the remainder). Using Russian activity data and fuel-based emission factors, the paper also presents BC emissions from diesel locomotives and ships, off-road engines in industry, construction and agriculture, and generators. The study also factors in the role of superemitters in BC emissions from diesel on-road vehicles and off-road sources. The total emissions from diesel sources in Russia are estimated to be 4~~8~~9 Gg of BC and 17 Gg of organic carbon (OC) in 2014. Off-road diesel sources emitted 5~~7~~8 % of all diesel BC in Russia.

1 Introduction

Black carbon (BC), a component of particulate matter (PM), may be the most powerful contributor to climate change after carbon dioxide (Bond and Sun, 2005; Bond et al., 2013). BC emissions cause significant warming effects through direct light absorption, interaction with clouds, and reduced albedo on snow. In polar regions especially, BC plays an important role because BC accumulation on snow and ice facilitates the absorption of solar radiation, increases air temperature, and accelerates snow and ice melting (Warren and Wiscombe, 1980; Hansen, 2003; Quinn, 2008; Quinn et al., 2011; Koch and Del Genio, 2010; Bond et al., 2013).

BC, as a major component of diesel PM, also has adverse health impacts (WHO, 2012). Chronic exposure to PM is associated with a range of diseases and can cause premature death from cardiopulmonary disease and lung cancer (Pope III et al., 2011). Exposure to PM emissions is the ninth leading factor of premature death globally (Lim and et.al., 2012); the World Health Organization estimates that PM pollution accounted for 3.1 million deaths in

2010 (WHO, 2013). According to the Global Burden of Disease study, ambient PM pollution caused more than 100,000 premature deaths in Russia in 2013 (GBD, 2016).

BC is a product of incomplete combustion of fossil fuels, biofuels and biomass. In 2000, diesel BC emissions accounted for 25-30 % of all energy-related BC emissions worldwide (Bond et al., 2013). In Europe, North America, and Latin America, diesel transport, both on- and off-road, accounts for about 70 % of all energy-related BC emissions. Over the decade, diesel production has risen by 10 % (Minenergo, 2015). Diesel is important to BC for two additional reasons. First, diesel combustion results in a high share of BC compared with other emissions sources. Second, there are well-established control technologies and policies to reduce emissions from diesel combustion. In fact, this study finds that Russian emissions are lower than many previous studies specifically because we are able to account for the impact of the emission standards in reducing emissions.

Russia is the second largest producer of crude oil in the world (IEA, 2015b); likewise, it is a large producer and consumer of diesel fuel. Despite the large diesel consumption of Russia, the country has historically represented a significant gap in our global understanding of BC emissions.

Inventories are important in developing mitigation policies and improving our understanding of global climate in models. Global or regional emission inventories, however, tend to rely on simple assumptions for emission calculations because country-level data might not be available. The aim of this paper is to present a detailed BC emission inventory from diesel sources in the Russian Federation for the base year 2014. Previous studies reporting BC emissions from Russian diesel sources were estimated primarily by combining fuel consumption with fuel-based emission factors. This paper instead draws on detailed data about the Russian vehicle fleet, annual mileage by vehicle category, the usage of emission controls on off-road vehicles, and other factors such as the existence of super-emitters in the on-road diesel fleet.

This study focuses on BC emissions from diesel sources only per the parameters of the United States Environmental Protection Agency's (US EPA) Reduction of Black Carbon from Diesel Sources in the Russian Arctic project, which is part of the USG Arctic Black Carbon Initiative (EPA, 2016).

2 Methodology

2.1 Emission standards for diesel engines

Russia has adopted the vehicle emission standards developed by the United Nations Economic Commission for Europe (UNECE). Specifically, Russia introduced Euro 2 standards in 2006 (Supplement Table S1). Emission standards in Russia apply to both domestically produced and imported vehicles. The minimum emission standard in 2014 was Euro 4 for cars and Euro IV for trucks and buses. As of January 2016, the minimum standard is Euro 5/Euro V. Russia has no official plans to move to the Euro 6 standard.

Russia has also adopted the European standard for PM emissions for off-road vehicles used for agriculture and forestry (these off-road standards are broken into "Stages" in the European system). According to Technical Regulation 031/2012, agricultural and forestry off-road vehicles should meet the UNECE standard (Stage III) (Eurasian Commission, 2012). However, in the baseline year for this inventory (2014), there was no PM emission standard for agricultural vehicles in Russia. Additionally, the implementation of this new standard appears to be weak. Apart from agriculture and forestry, equipment in other sectors in Russia is not obliged to comply with any PM emission standards (Eurasian Commission, 2011b).

2.2 Methodology for emission calculations from on-road vehicles

The European COPERT model (COmputer Programme to calculate Emissions from Road Transport) calculates emissions from on-road vehicles. The European Environmental Agency (EEA) supported the development of COPERT. EEA member countries use this free software for official road transport emission inventory preparation (Emisia, 2015). Twenty-two countries of the European Union use the model to calculate road transport emissions (Ntziachristos et al., 2009). In this study, we use the COPERT 4 model (version 11.3).

Diesel vehicles in the COPERT model are classified into four large groups: passenger cars, light commercial vehicles (LCVs), heavy-duty trucks, and buses. In the model, exhaust BC emissions from vehicles depend primarily on the following: 1) the number of vehicles on the roads, 2) emission factors, and 3) average number of kilometers traveled.

The COPERT model uses European-specific emission factors and allows users to input country-specific emissions factors. The Russian Scientific Research Institute for Automobile and Transportation (NIIAT) developed two methodologies for calculating emissions from on-road transport (NIIAT, 2006, 2012). They are based on the simplified EMEP/CORINAIR approach (now called EMEP/EEA Air Pollutant Emission Inventory Guidebook).

NIIAT has developed PM emission factors for Russian vehicles based on vehicle emission test data for both Russian and foreign vehicles. Based on vehicle driving tests conducted with Scientific and Research Vehicle Testing Center, NIIAT has developed emission factors for Russian models. For foreign-made vehicles, NIIAT relies on data from the European EMEP/CORINAIR guidebook. Thus, Russian-specific emission factors for $PM_{2.5}$ in the NIIAT methodologies are based on the average for every vehicle type and emission class on Russian roads. Supplement Table S2 provides the emission factors for the following categories of diesel vehicles: cars, light trucks and buses (LCVs), heavy-duty trucks, and buses on three types of roads (urban, rural, and highways).

We derive BC/PM ratios from the EEA emission guidebook (EEA, 2013). The COPERT model can also directly calculate emissions of elemental carbon (EC) and organic carbon (OC). In European emission studies, EC is assumed to be equal to BC for transport due to the nature of the combustion processes.

Diesel engines emit BC emissions in two distinct stages of operations – cold start and hot operation. The COPERT and the NIIAT models use different approaches to calculate cold start emissions. However, in their study of BC emissions from diesel vehicles in the Murmansk Region, Evans et al. showed that both methodologies yield very similar total emissions (Evans et al., 2015). As a result, in this study we do not analyze hot and cold emissions separately and present only the total emissions.

2.3 Methodology for emission calculations from off-road engines

BC emission calculations from off-road diesel engines can be expressed by Eq. 1:

$$BC\ emissions = fuel(kg) * PM\ emission\ factor\ (g\ kg^{-1}) * BC/PM\ ratio \quad (1)$$

We used Formula 1 to calculate emissions from off-road sources listed in Section 5. Table 1 presents PM emission factors and BC/PM speciation ratios used in this study.

Though emission factors reported in the literature could be different from those in the emission guidebook, we use the EEA emission factors for consistency. The advantage of using this approach is that the guidebook reports emission factors for equipment without emission controls. Since the majority of diesel off-road vehicles and equipment is old and Russia does not regulate particulates from off-road diesel sources, we assumed that there are no emission controls on most of the off-road diesel sources. Some small percentage of imported engines might have emission controls.

3 Diesel consumption

3.1 Production of diesel fuel

The Russian Federation is the second largest producer of crude oil in the world, producing 13 % of total world oil in 2014 (IEA, 2015b). It is also a large producer of diesel fuel as well. The country increased diesel production from 70 million metric t (Mt) in 2010 to 77 Mt in 2014. Importantly, over the same time frame, Russia implemented standards that improved the quality of its diesel fuel, reducing sulfur content (Figure 1). Sulfur content of diesel fuel is an important factor in emission reductions. Diesel with high sulfur content (measured in parts per million or ppm) can destroy emission control devices, such as particulate filters. Availability of low sulfur diesel is an important prerequisite for the introduction of more stringent vehicle emission standards.

The share of Euro 5 diesel (with sulfur content of 10 ppm, otherwise known as ultralow sulfur fuel) increased from 6 % in 2011 to 50 % in 2014 (Fedstat, 2015e). By the end of 2015, according to an estimate of the Russian Ministry of Energy, Euro 5 diesel accounted for 82 % of the total diesel production (Government of Russian Federation, 2015). Russia exports more than half of diesel produced; the quality of exported diesel is lower than that of the diesel used domestically.

Russia banned the domestic sale of lower grade diesel in 2013. In 2014, only Euro 4 (50 ppm) and Euro 5 (10 ppm) fuels were legal to sell for on-road transport (Eurasian Commission, 2011a). However, compliance with this standard is not universal. Rosstandard, a government agency responsible for fuel quality control, found that the sulfur content exceeded the maximum allowable content in 21 % of the fueling stations checked in 2014 (Rosstandard, 2015). Though Russia banned high-sulfur diesel, the demand for cheap diesel remains because older engines, especially off-road vehicles, can save money by using high-sulfur diesel.

3.2 Diesel consumption

According to the Russian Ministry of Energy, Russia's domestic diesel supply was 32 Mt in 2014 (Minenergo, 2015). Euro 4 and Euro 5 diesel accounted for 88 % (28 Mt) of the domestic diesel supply in 2014, which is more than enough to fuel all the Euro 4 and Euro 5 vehicles. In other words, fuel quality alone likely does not impact emissions.

On-road transport is the largest consumer of diesel, but estimates vary. There are several data sources on diesel consumption by on-road transport, including official statistics, officially commissioned fuel balances, data from international organizations, and bottom-up estimates.

The Russian fuel consumption statistics are based to a large extent on reports from enterprises. Only medium and large enterprises must report their fuel use to the Federal Statistics Service (Fedstat). Large companies must complete the so-called TER 4 form on fuel consumption "Fuels and energy inventory, inflow, consumption, and balance at the end of the reporting period." The aggregated data are publicly available (Fedstat, 2015g, d). Another data source is the TER 11 form on fuel consumption by unit of production; however, this information is not available for all sectors. Small businesses are not required to submit this information, yet they employ 11 million people (Fedstat, 2015h, a, b, c) and produce more than 20% of goods and services (GKS, 2015b). Neither is there official information on diesel consumption by vehicles owned by individuals (for example, on diesel sold at fueling stations). As a result, the official data on diesel consumption by on-road vehicles are incomplete. However, large enterprises do not need to conduct surveys to analyze their sales, so the diesel data likely underreport diesel consumption by individuals and small enterprises.

According to Fedstat, vehicles owned by medium and large enterprises consumed 12.7 Mt of diesel in 2013 and 12.2 Mt in 2014 (Fedstat, 2015d). The International Energy Agency (IEA) reports that Russia's on-road transport consumed 11.2 Mt of diesel in 2013 (IEA, 2015a). Both assessments likely underestimate the diesel consumption by on-road vehicles in the country.

There are several independent bottom-up estimates of diesel consumption by on-road transport. The Russian research company Petromarket estimated that on-road vehicles consumed 23.5 Mt of diesel in 2013 and 24.5 Mt in 2014. Analytical agency Avtostat calculated that on-road vehicles consumed 25.8 Mt of diesel in 2014 (Avtostat, 2015b). Avtostat also estimated that vehicles in the European part of the Russian Federation consumed 70 % of fuel used by on-road transport. However, their assessments both have their limitations because they do not use a fuel balance approach; in other words they do not match diesel consumption by on-road vehicles and off-road engines with the production of diesel fuel in the country.

In this paper, we use data from the Russian Center for Energy Efficiency (CENEf), which uses a balance approach for assessing the fuel consumption. CENEf is a leading Russian energy research organization commissioned by the Ministry of Energy to develop fuel balances. It has access to multiple types of fuel statistics and uses a sophisticated transport model to calculate fuel consumption by on-road vehicles. CENEf prepares the Russian energy balances by integrating the reporting forms from medium and large enterprises and bottom up calculations to cross-check allocations across sectors. CENEf also ensures that supply of crude oil and oil products balances demand. Table 2 shows the diesel consumption in 2014 (in thousand metric tons (kt)).

CENEf estimated that the total diesel consumption in the country was about 32 Mt in 2014. On-road vehicles used 22.2 Mt of the final diesel consumption. Other significant consumers of diesel are rail, diesel generators and boilers, industry, and agriculture.

We did not attempt to estimate the military fuel consumption. Military might be a large consumer of diesel in the country; however, none of the Russian experts were able to provide fuel estimates. We might assume that military consumption is spread throughout all sectors, but we cannot verify this assumption. We should note that the military uses diesel with high sulfur content. Most of the military equipment is designed for high-sulfur fuel; Russia prohibits low-sulfur diesel for military goals. From 1 January 2015, the intergovernmental standard GOST 305-2013 requires the 2000 ppm sulfur content for the defense orders (Rosstandard, 2013).

4 On-road transportation

4.1 Activity data

Registered fleet

We use the complete vehicle registry containing information from about 49 million records to analyze on-road transport in Russia. The Russian analytical agency Avtostat provided the official registry with detailed vehicle information on fuel type and emissions standard (Avtostat, 2015c).

According to Avtostat data, 40.83 million passenger cars were registered in Russia as of January 2015. The share of diesel passenger cars was 4.2 % (Avtostat, 2015c). The popularity of diesel cars is growing in Russia, representing 7-8% of new sales. ~~As Russia does not have large-scale production of diesel passenger cars, o~~Only 2 % out of the 1.7 million diesel cars registered in Russia in 2014 were Russian models. All other diesel cars were imported or produced in Russia by foreign companies. ~~Overall, foreign-make cars, both gasoline and diesel, constitute about 50 % of the passenger fleet.~~

Among the 3.96 million light commercial vehicles (LCVs) registered in 2014, 28 % used diesel. The share of diesel LCVs in new sales is also growing, and every other LCV sold in Russia is equipped with a diesel engine.

The heavy-duty truck fleet consists of 3.73 million vehicles. There were 2.32 million registered diesel trucks (62 % of the truck fleet) registered in 2014. The fact that not all heavy-duty trucks use diesel plays an important role in emission calculations. Studies that assume that all heavy-duty trucks use diesel tend to overestimate their emissions.

In recent years, 98 % of new trucks run on diesel. Russian-make heavy-duty trucks constitute about two thirds of the diesel truck fleet. We grouped all diesel trucks into four groups depending their weight: <7.5 t (35 % of the truck fleet), 7.5-12 t (19 %), 12-14 t (9 %) and above 14 t (37 %) (RAMR, 2012). This classification is consistent with the COPERT and NIIAT models.

There were 0.39 million buses registered in Russia in 2014. Forty-five percent of buses run on diesel. Russian brands made up about two thirds of the diesel bus fleet. We group all diesel buses into three groups depending on their size: small buses (75 % of the bus fleet), medium (12 %), and large and extra-large (13 %).

Active vehicles

Russian experts point out that the official vehicle registry does not correctly reflect the number of vehicles on the roads (Donchenko, 2013, 2016;Avtostat, 2016, 2015a). A significant share of the fleet is very old: 28 % of cars and

49 % of LCVs are older than 10 years; and 36 % of trucks and 23 % of buses are older than 20 years (Avtostat, 2015c). The fact that these vehicles are still registered does not mean that they are in working condition. For emission calculations we assess the "active fleet," that is, the vehicles that are used regularly.

To estimate the share of active vehicles, Avtostat used annual data from the Russian Union of Insurers about the number of insurance policies (stickers) issued. The total number of stickers issued is a good proxy for the active fleet because it is illegal to use vehicles without insurance stickers. According to Avtostat estimates, the share of active passenger cars is 76 % of the number of registered cars; for LCVs, buses, and trucks these shares are 80 %, 49 %, and 64 %, respectively. Using the age distribution of diesel and gasoline vehicles, we calculated the share of active vehicles in the diesel and gasoline fleets. Table 3 shows the summary of our calculations. Supplement Table S3 shows the number of active diesel vehicles by type and emission standard in Russia in 2014.

Distribution by emission standard

Emission standards and fleet upgrades play an important role in emission reductions. For example, NIIAT estimated that from 2006, when Russia first had introduced emission standards, to 2011, PM emissions from on-road vehicles in the country dropped by 30 % (Donchenko, 2007, 2013). This occurred even as the number of registered trucks and cars increased by 12 % and 36 %, respectively (GKS, 2014a).

Figure 2 shows the distribution of diesel vehicles by emission standard. Because gasoline vehicles emit practically no BC, gasoline vehicles were differentiated from diesel vehicles in the on-road fleet and not analyzed in this study.

Superemitters

The concept of superemitters is not well defined in the literature. The common approach, however, is to define superemitters as vehicles that have very high emissions compared to regular vehicles (sometimes referred to as "high emitting vehicles"). In the vehicle testing studies, a cutoff level is used to determine the share of superemitters. For example, in Thailand, Subramanian et al. selected 4.7 g kg^{-1} as the cutoff for all diesel superemitters in their Bangkok study (Subramanian et al., 2009). In Chile, Faiz et al. used the cutoff level of 7.5 g kg^{-1} for buses in their Santiago study (Faiz et al., 1996).

For national emission inventories, the cutoff approach cannot be used for emission calculations. The commonly accepted approach is to define the share of superemitters in the fleet and use specific emission factors for these high-emitting vehicles. As a result, this study uses assumptions about the share of superemitters in the diesel fleet to provide a more realistic emission inventory.

Superemitters should be represented in inventories because they are responsible for a large share of emissions. For example, Ban-Weiss et al. (2009) measured emissions from 226 diesel trucks driving through a highway tunnel in California and found that 10 % of the highest-emitting trucks were responsible for about 40 % of total BC from trucks. In Beijing, Wang et al. (2011) found that approximately 5 % of the trucks are responsible for 50 % of the BC emissions. In Slovenia, a study of 139 individual vehicles of different types showed that 25 % of the highest-emitting diesel vehicles produce 63 % of the BC emissions (Ježek et al., 2015). Preble at al. found that 20 % of trucks emit 80 % of the BC emissions from the Port of Oakland truck fleet (Preble et al., 2015).

Despite that superemitters emit a significant share of total emissions, there is a limited number of studies on their share of superemitters in the diesel fleet. For example, Subramanian et al. (2009) estimated that the fraction of superemitters in the studied diesel fleet in Bangkok is 15 %. In their study of BC and PM emissions from 251 trucks in California, Ban-Weiss et al. (2009) found that about 13 % of the diesel fleet are superemitters. Bond et al. (2004) assumed with a high uncertainty that the share of superemitters for countries "similar" to the United States is 5 %. A recent study by the California Air Resources Board shows that 8 % of trucks were classified as high emitters (emitting over 5 % opacity) from a sample of over 1800 truck tests (CARB, 2015). We should note that US EPA no longer uses the concept of superemitters to estimate vehicle emissions (EPA, 2015).

There are no known studies on superemitters in Russia. Bond et al. (2004) assumed that the share of superemitters in Eastern Europe and the former Soviet Union is 10 %. This estimate also was used in other studies (Yan et al., 2011;Yan et al., 2014). This study uses the ~~same~~ assumption that the share of superemitters in the Russian diesel fleet is 15%~~about the share of superemitters in Russia~~.

We use a logistic function from (Yan et al., 2011) to represent the rate at which normal vehicles become superemitters (Eq. 2).

$$fr\ (s) = \frac{gain}{1+\exp[\alpha\ \mathrm{sup}(1-{}^{s}/_{L50\ \mathrm{sup}})]} \qquad (2)$$

where *fr* is the fractional rate at which normal vehicles become superemitters (fraction per year); *gain* is the maximum rate of superemitter transition, a_{sup} determines the slope of the transition curve with age, *s* is vehicle age, and $L_{50,sup}$ is the vehicle life at which the rate becomes half the maximum.

Since retired (inactive) vehicles were already from the registry, we modified the *gain* parameter in the formula to obtain the number of superemitters, which equal 15~~0~~ % of the total active diesel fleet.~~, to be consistent with previous studies (Yan et al., 2011;Yan et al., 2014;Bond et al., 2004)~~. In this study, the parameters of the formula are as follows: a_{sup} = 5.5; $L_{50,sup}$ = 5.0; and *gain* = 0.024~~162~~.

The share of superemitters in the fleet depends on the vehicle age. Using Formula 2 we calculated that this share is less than 3~~1~~ % for vehicles less than 5 years old, close to 18~~0~~ % among 10 year-old vehicles, and 50~~25~~ % for 20 year-old vehicles. Since the age distribution varies by vehicle type, using Formula 1 we calculated the fraction of superemitters in the diesel fleet: ~~6.4~~10 % for cars, ~~11.4~~17 % for LCVs, ~~12.9~~19 % for trucks, and ~~10.2~~15 % for buses. As mentioned above, the overall share of superemitters in the diesel fleet is 15~~0~~ %.

Using the information on diesel consumption by vehicle type and the percentage of superemitters in the fleet, we calculated that superemitters consumed 2100 t of diesel or 9.5 % of total diesel consumption by on-road vehicles. Based on Yan et al. (2011) we assume that PM emission factors for diesel on-road superemitters is 8.31 g kg^{-1} for older engine superemitters (Euro 0 and Euro 1) and 2.92 g kg^{-1} for newer engine superemitters (Euro 2–Euro 5). We also tested an assumption from {McClintock, 2011 #503} that the emission factors of superemitters are six times higher than the average of the on-road diesel fleet. Using Russian-specific emission factors, we assume that the PM emission factor for superemitters is 0.39 g km^{-1} for cars, 0.59 g km^{-1} for LCVs, 0.8 g km^{-1} for trucks, and 1.31 g km^{-1} for buses. These two approaches yield very similar results (difference is about 3 %).

~~Similarly, w~~We assume that the share of superemitters in the off-road fleet is the same as in on-road one (15 %). Following Bond et al. we assume that the PM emission factor for off-road superemitters is 12 g kg^{-1} and OC/BC ratio is 0.21 (Bond et al., 2004).

Annual distance traveled

The annual average distance traveled is one the most important parameters in the COPERT model. We use several sources to estimate the annual number of kilometers traveled by type of vehicles in Russia. NIIAT developed a methodology for assessing the residual value of vehicles based on their age and kilometers traveled (NIIAT, 1998). This methodology provides estimates of the annual average distance traveled by type of vehicles, country of production, and road type. In its emission calculation methodology (2008, 2012), NIIAT estimated the average annual distance traveled for the total fleet. Avtostat conducted an extensive study of vehicle activity and estimated the average annual kilometers traveled by Russian and foreign-made cars. Avtostat also provided its estimates on average kilometers traveled by LCVs, trucks, and buses. We use the Avtostat assumptions for emission calculations. Table S4 shows the assumptions on average of annual kilometers traveled in different models/methodologies. Supplement Table S5 provides details on our assumptions on annual kilometers traveled by vehicles by Euro class.

The average speed is assumed to be 25 km h^{-1} in cities, 40 km h^{-1} on rural roads, and 90 km h^{-1} on highways. The assumption on the speed in cities is based on actual speed in Moscow and other large cities. The assumptions on the average speed on rural roads and highways are based on maximum allowable (standard) speed on these types of roads in Russia. The share of vehicle-kilometers traveled (vkt) on urban roads is taken from the ICCT Roadmap model (ICCT, 2015)~~.~~. The share of vkt on urban roads is 75% for cars, light commercial vehicles, and buses and 50% for trucks. The rest of VKT is divided by 40:60 between rural roads and highways.

4.2 Emissions calculations

BC emissions from diesel on-road vehicles were calculated using the COPERT 4 model with NIIAT emission factors. Superemitters were excluded from our initial emission calculations with the COPERT model. Instead, emissions from superemitters were calculated using Formula 1 and added to COPERT results.

Table 4 shows the results of emission calculations from active diesel vehicles. Heavy-duty trucks emitted 60~~8~~ % of all on-road diesel BC, while passenger cars emitted only 5~~4~~ %.

The results show that superemitters emitted 8.~~28~~9 Gg of BC or 43~~0~~ % of all diesel on-road BC emissions. The role of superemitters in emissions by type of vehicles varies from to about ~~3~~40 % for buses ~~to 47 %~~and heavy-duty trucks to ~~2~~44 % for cars and 48% for light-duty vehicles.

The total BC emissions from on-road diesel vehicles are estimated at 20.7~~51~~ Gg in 2014. Heavy-duty trucks emitted ~~70~~60 % of all on-road diesel BC emissions. We also estimated that normal vehicles have emitted ~~6.08~~5.6 Gg of OC emissions, and superemitters produced an additional 4.9~~3.33~~ Gg of OC in 2014 (see Supplement Table S6 for details).

As mentioned above, it is important to separate diesel vehicles from gasoline ones, exclude vehicles that are not in use, and factor in superemitters. If one assumed that all heavy-duty vehicles use diesel, BC emissions from trucks alone would be 3~~6~~9.~~79~~66 Gg of BC, significantly overstating the total. Likewise, BC emissions from all registered diesel vehicles (as they appeared on the vehicle registry) are 2~~7~~9.~~31~~09 Gg. Emissions from the adjusted fleet without accounting for superemitters would be ~~14.85~~16.26 Gg (See Supplement Tables S7-S9 for details).

5 Off-road diesel sources

5.1 Rail

The total length of railroads is 86 000 km, and about 60 % of them are electrified (GKS, 2014b). Given the size of the country, the density of railroads is low compared to other European countries. Rail cargo turnover was 2301 billion tkm in 2014, which is almost ten times larger than that of road transport (247 billion tkm). In 2013, diesel locomotives transported almost 15 % of all rail cargo (GKS, 2014b).

The Russian Railway Company (RZhD, based on the Russian acronym) is the largest owner of diesel locomotives in the country. RZhD owned 10 400 electric locomotives and 10 200 diesel locomotives in 2013, including 3500 line haul and 6100 shunting locomotives (Balabin and Evpakov, 2013). In addition to RZhD's stock, large industrial companies also own about 12 000 locomotives to form trains. In 2012, RZhD started using Euro 3 diesel (350 ppm) for its diesel locomotives (RZhD, 2013).

The locomotive fleet is old: about 50 % of long-line haul locomotives are more than 15 years old. Diesel locomotives in Russia have no emission controls. The EEA guidebook presents the emission factors for diesel locomotives based on average European fleet (1.37 g kg^{-1}). Given that the Russian locomotives are older than those in Europe, we use the emission factor from Yan (2014) for locomotives without emission controls. Thus, we assume that the PM emission factor for diesel locomotives in Russia is 4.62 g kg^{-1}.

5.2 Domestic navigation and fishing

Domestic navigation and fishing represent different economic sectors but use similar combustion technologies. Liquid bulk ships, dry cargo carriers, and container ships mainly use heavy bunker fuel oil, while passenger ships, fishing boats, and tugs use diesel. Diesel ships tend to be smaller than those using bunker fuel oil. Almost all ships use diesel during maneuvering and while docked at shore. As a result, emissions from domestic navigation and fishing are presented in the same category.

Russia is a large marine state with the third longest coastline in the world. There are 67 sea ports in Russia; although only a few are ice-free in winter. The largest areas of maritime activity are the Baltic Sea, the Black Sea region, and the Far East. The Arctic region accounts for 5.6 % of cargo turnover, but its maritime activity is rapidly expending given the increasingly ice-free Northern Sea Route.

Most marine and fishing vessels in Russia are old. For example, over 70 % of river and lake vessels are older than 25 years (Mintrans, 2015). Similarly, over 80 % of fishing ships are over 20 years old (WCIOM, 2015).

The cargo fleet has been shrinking: there were 3830 sea-going vessels in 2000, 3514 in 2005, and 2712 in 2014. The number of river vessels decreased from 31 800 in 2000 to 21 800 in 2014 (GKS, 2015b).

Ships were estimated to have used 526 kt of diesel in 2014. This does not include military consumption, which could be very significant. Ships were assumed to have no emission controls since Russia has no emission standards for them.

5.3 Agriculture

According to estimates from the Ministry of Agriculture, agricultural companies in 2014 owned 420 000 agricultural tractors, 153 000 harvesters and 22 000 other motor vehicles (Ministry of Agriculture, 2015). In Russia, the agricultural fleet has been shrinking (Ministry of Agriculture, 2015). For example, there were 15 000 fewer tractors in 2014 than in 2013. In 2014, the retirement rate for tractors was 5.1 % while the replacement rate was 3.2 % (GKS, 2015a).

Tractors produced in Russia, Belarus, and Ukraine constitute over 90 % of the tractor fleet, and the majority of tractors are over 10 years old (Ministry of Agriculture, 2015). As a result, the availability of emission controls is very limited. Moreover, until recently, there were no emission standards for agricultural vehicles in Russia. Because of new emission standards for agricultural vehicles in Russia, emissions may possibly drop in the future.

Since Russia has limited production of agricultural tractors (about 3 % of new sales), foreign-made agricultural machinery dominates new sales (Agroinfo, 2015). The share of used tractors in the total imports was 20 % in 2014. Tractors imported from Western countries were assumed to have emission controls; however, their share in the total agricultural fleet is very small (no more than 5 %).

We assume that the distribution by emission standard is as follows: 95 % is Stage 0 (without emission controls) and 5 % meets Stage 2 standards.

5.4 Industry

Mining

The mining sector consumes about half of the industrial diesel. Russia is a major mineral and coal producer. Russia produced 357 Mt of coal in 2014 and is also a leading global producer of many other mined commodities, including aluminum, copper, iron ore, lead, and nickel, among others (USGS, 2016).

Open-pit mining is widespread in Russia due to its relatively lower production costs. Sixty-five percent of the coal produced in 2014 was in open-pit mines (EMIS, 2014;GKS, 2015b). Mining trucks consume 70–80 % of the diesel at open pit mines both due to their large engines and the fact that mining operations continue nonstop. On average each truck operates well over 6300 h yr^{-1} (Mining Magazine, 2007). The Belarusian company BELAZ supplies the majority of the largest mining trucks (Petrovich et al., 2013), and most BELAZ trucks are equipped with Cummins and MTU engines. The average life of mining trucks is short: BELAZ trucks operate for 5–7 years (Zvonar, 2010), while Caterpillar mining trucks operate for 9-12 years (Anistratov, 2013).

Russia has no emission standards for off-road mining vehicles, and, as a result, Western companies can supply engines without emission controls. For example, about 88 % of Cummins engines in Russia have no controls, and the remaining 12 % meet US EPA Tier 1 requirements (Mueller, 2014). A small population of Caterpillar and Komatsu trucks also meet Tier 1 or Tier 2 requirements.

The role of the mining industry in diesel consumption and BC emissions is especially important in the Russian Arctic. For example, in their study of BC emissions in the Arctic, Evans et al. (2015) found that the mining industry emits about 70 % of all diesel BC emission in the Murmansk Region. A second study on BC emissions in the Russian Arctic found that the mining industry emits 80 % of BC emissions from combustion in Russia's Arctic zone (Morozova, 2015).

We assume that 88 % of engines in the mining industry are Tier 0 (1991–Stage 1) and 12 % are Tier 1 (Stage 1).

Construction

The construction industry is an important sector of the Russian economy. In 2013, 5.7 million people were employed in construction (8 % of the labor force). Over 226 000 construction companies worked in Russia in 2014 (GKS, 2015b), indicating that most of them are small businesses.

The construction industry uses more varieties of diesel engines than any other sector of the economy. Most of construction equipment is old and lacks emission controls. About 30-50 % of these excavators, loaders, bulldozers, and graders have reached their end of useful life (Rosstat, 2014). Though up to 60 % of construction machinery is imported depending on type of vehicles, they do not necessarily have emission controls. We assume that the distribution by emission standard is as follows: 90 % of construction machinery is Stage 0 (without emission controls) and 10 % have some emission controls.

Other industry

Other types of industries that use diesel include production of iron, steel, non-ferrous metals, chemicals, machinery, food, paper, wood products, textiles, and other types of goods. In these industries, a huge variety of diesel machinery and equipment exists and is assumed to be primarily heavy industrial equipment with no emission controls.

5.5 Diesel generators

About 60 % of Russia's territory is not connected to the centralized electricity grid (Suslov, 2012). Twenty million people live in these off-grid areas, which include cities, towns, and villages (Zatopliaev and Redko, 2004). Stationary diesel generators produce electricity in small isolated grids in remote locations.

About 47 000 diesel generators provide electricity; 12 000 of these are in the northern part of the country. The typical generator power capacity ranges from 100 kW to 3.5 MW. At the beginning of the 2000s, the installed capacity of diesel generators was about 17 million kW or 8 % of the total installed capacity in Russia (Minenergo, 2012). According to the Russian Statistical Service, large diesel power stations generated 4500 GWh of electricity in 2014 (Fedstat, 2015f).

In addition to electricity generation, diesel can be used to produce heat. Diesel boilers and heat pumps are used in areas without centralized district heating. The process of external combustion in boilers is quite different from that in diesel engines, and as a result PM emission factors and BC/PM ratios for external combustion are lower than those from internal combustion engines (Bond et al., 2004).

In 2014 diesel generators used 1.034 Mt of diesel and heat plants used an additional 315 kt.

6 Results of BC emission calculations

Table 5 presents the results of emission calculations from off-road diesel sources in Russia as well as the total for on-road transportation in 2014. We estimate that all off-road sources emitted 28~~2~~.5~~9~~ Gg of BC and ~~5.3~~6.7 Gg of OC. The largest emission contributors in the off-road sector are ~~industry,~~ industry, locomotives, and ~~diesel generators~~agricultural machinery. This study also includes superemitters in the off-road diesel fleet. The role of superemitters in the off-road fleet is less important than for the on-road fleet due to differences in emission factors between normal engines and superemitters. We estimate that off-road superemitters are responsible for 23~~1~~% of BC emissions from off-road sources.

Rail is the largest source of off-road BC emissions because of outdated equipment and high emission factors, as well as the extensive use of diesel locomotives in off-grid parts of Russia. Industry is a large source because of the diversity of small uses without emission controls. Diesel generators without emissions controls produced more BC emissions than the mining industry because of the lack of emission controls and larger emission factors.

These results show that off-road diesel sources emit 5~~7~~8 % of the total diesel BC in Russia. These high levels of emissions from off-road sources are a result of the limited use of emission control technologies, a function both of the equipment age and the lack of regulations for new equipment. This contrasts with emissions from on-road vehicles, where standards were introduced a decade ago, and emissions have subsequently dropped. While consuming 70 % of the diesel fuel in the country, on-road vehicles produced 4~~3~~2 % of BC emissions in 2014.

7 Comparison with other studies

There have been several studies looking at BC emissions in Russia across a range of sectors, but the majority of these studies use fuel-based, mass balance approaches to calculating emissions. In previous studies, emissions from on-road transport were estimated based on the number of registered vehicles or in the best case on vehicles separated into a few emission standards. A limited number of studies have assessed the existence of control technologies and other detailed, real-world activity data. None of the studies accounted for superemitters in the fleet.

Table 6 below shows the result of several previous studies covering total anthropogenic BC emissions, emissions from transport or all diesel sources.

There are two wide categories of studies on Russian BC emissions. Emission estimates in the first category are based on fuel consumption, use global or regional emission factors, and mostly do not use Russian activity data. For example, Bond et al. (2004) combined fuel consumption data and application of combustion technologies and emission controls (Bond et al., 2004;Sarofim et al., 2009). Lamarque et al. (2010), updating the Bond data (2004), estimated that diesel engines are likely to be the fourth largest source of BC emissions in Russia after residential/domestic sources, forest fires, and industry (EPA, 2012b; Lamarque et al., 2010). The International Institute for Applied Systems Analysis (IIASA) uses the Regional Air Pollution INformation and Simulation (RAINS) model and Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants (ECLIPSE) model to estimate PM and BC emissions. BC emissions from transport were estimated to be 52 Gg in 2010 (Sand et al., 2016).

The second category of Russian BC studies is based on Russian activity data, where Russia-specific emission factors were used for on-road transport and/or bottom-up fuel consumption data. Some of these studies were completed in the framework of BC mitigation efforts in the Arctic. In 2015, Russia submitted its first report to the Arctic Council on BC and methane emissions reductions. The total Russia-wide BC emissions were estimated to be 358.5 Gg in 2013 (MNRE, 2015). Transport was not determined to be a significant source of BC emissions (7.7 Gg or just 2 % of the emissions). An international group of scientists led by the US Department of Energy estimated BC emissions in the Russian Arctic and in Russia from anthropogenic sources (Huang et al., 2015). Drawing on local Russian information, Russian BC emissions were estimated to be 224 Gg in 2010. Using vehicle registry data, BC emissions from transport were estimated to be 45.3 Gg (Huang et al., 2015). The authors assumed that all registered vehicles are actively used and all vehicles use diesel fuel. The paper does not present the vehicular emissions by vehicle type or emission standard.

NIIAT estimated that Russian on-road vehicles emitted 53.9 Gg PM in 2006 (Donchenko, 2007) and 38.5 Gg PM in 2011 (Donchenko, 2013). NIIAT used the Russian PM emission factors and, until recently, had not calculated BC emissions. NIIAT used detailed information about the number of diesel vehicles and adjusted the registry to reflect the share of the active fleet. NIIAT does not account for superemitters in emission calculations.

Evans et al. (2015) used the IEA diesel data and estimated BC emissions from all diesel sources, including diesel transport, in Russia. Using fuel-based emission factors from the EEA emission guidebook and NIIAT emission factors, BC emissions from on-road transport were estimated to be about 20.0 Gg (Evans et al., 2015). Similarly, Kholod and Evans (2016) use the Global Change Assessment Model (GCAM) to build a forecast for BC emissions from on-road transport in Russia. Total BC emissions from on-road transport were estimated to be about 20.0 Gg in 2015. The model, however, does not calculate emissions from vehicles by emission standard, which is important for developing emission reduction strategies.

We can conclude that the results of the emission calculations presented in the current study are close to those studies that used detailed Russian activity data (number of active diesel vehicles, annual average distance traveled, and Russian emission factors). The advantages of the current study are that we present the BC emissions from on-road transport by vehicle types and emission standards, factor in superemitters, and also present OC emissions from on-road vehicles and off-road diesel sources.

8 Uncertainty

There are two major sources of uncertainty in BC emission inventories: 1) emission factors and 2) activity data. Emission factor uncertainty includes uncertainties in PM emission factors for normal vehicles and superemitters and BC/PM speciation ratios. NIIAT does not report the uncertainty in PM emission factors for on-road vehicles. In COPERT, the uncertainty for PM emission factors is estimated to be 20–30 % (Kouridis et al., 2010). Uncertainty in PM emission factors for off-road sources is 30-60 % for agricultural vehicles, 25-50 % for ships, and an order of magnitude for industry (EEA, 2013).

~~Uncertainty in BC/$PM_{2.5}$ speciation ratios for on-road vehicles is 5–10 % for light-duty vehicles and 20 % for heavy-duty engines. The speciation ratio uncertainty for off-road diesel sources is 20 % (EEA, 2013). The speciation ratios are not a major source of uncertainty in emission inventories for diesel BC sources.~~

Activity data also present uncertainties because of uncertainties in underlying surveys or estimation methodologies. This includes data on fuel consumption by sector, distribution by vehicle type, annual number of kilometers traveled, and assumptions about emission controls. Fuel data differ by a lot, as well as the average annual distance traveled. The distribution by vehicle type and controls for on-road transport is less uncertain. Off-road uncertainty on emission controls is larger because more emission controls may exist than was assumed. We use several approaches to minimize uncertainties in the activity data, including multiple approaches to data collection, cross-checks with the literature, and expert judgments.

Uncertainty in BC/$PM_{2.5}$ speciation ratios for on-road vehicles is 5–10 % for light-duty vehicles and 20 % for heavy-duty engines. The speciation ratio uncertainty for off-road diesel sources is 20 % (EEA, 2013). The speciation ratios are not a major source of uncertainty in emission inventories for diesel BC sources.

Our data on fuel consumption are based on bottom-up calculations and are close to the Russian official statistics. While there is uncertainty in the distribution between economic sectors, the total domestic diesel supply is well determined.

Assumptions on emission controls do not significantly contribute to uncertainties in emissions because about 90–95 % of off-road diesel engines is assumed to have no emission controls. However, real emission factors for Russian diesel sources are not well understood. For on-road vehicles, the distribution by emission standards is well determined based on the registry. The key uncertainty here is the assumption of the share of active vehicles.

Another source of uncertainty is the share of superemitters in the on-road and off-road fleets. For emission calculations, the share of superemitters is assumed to be 15~~0~~ %. This number is to some extent arbitrary because it was determined based on a small number of studies. In addition, heavy-duty trucks are designed to meet emissions limits up to a specified maximum loading, and overloading can significantly increase the share of high-emitting vehicles (World Bank, 2014). There is evidence that Russian drivers tend to overload their trucks, especially on the long-haul routes, to save time and increase their short-term profit. According to the Russian Federal Road Agency, 30–40 % of heavy-duty trucks are overloaded on average by 45 % (Avtodor, 2015). As a result, the share of superemitters in the truck fleet might be ~~much~~ higher.

For on-road vehicles, three major sources of uncertainty were considered: the share of superemitters in the fleet, average annual distance traveled, and emissions factors for normal vehicles and superemitters. Supplement Table S10 shows the assumptions for uncertainty calculations for on-road vehicles.

The central value of BC emissions from on-road vehicles in 2014 is 20.7 Gg with an uncertainty range of -10.2 Gg and + 7.3 Gg. The central value of OC emissions is 10.5 Gg with an uncertainty range of -4.2 Gg and + 3.2 Gg. The uncertainty in BC emissions from off-road sources is estimated in the range from 19.2 Gg to 42.1 Gg (or -33%/+48%) with the central value of 28.5 Gg. OC emissions from off-road engines are in the range from 4.5 Gg to 9.8 Gg with the central value of 6.7 Gg.

The total emissions from diesel sources in Russia are estimated to be 49.2 Gg of BC and 17.2 Gg of OC in 2014.

9 Conclusions

In this paper, we estimate BC and OC emissions from diesel sources in Russia. We use detailed vehicle registry data containing information from about 49 million records to analyze on-road transport in Russia. We distinguished diesel vehicles from gasoline ones, estimate the share of active vehicles in the fleet, use detailed information on distribution by vehicles types and emission standards, and use Russia-specific emission factors for emission calculations. This study also factors in the role of superemitters in BC emissions from on-road diesel vehicles. Emissions from on-road diesel vehicles are estimated at 200.75 Gg of BC and 9.410.5 Gg of OC in 2014. Heavy-duty trucks emitted 7060 % of BC, while diesel passenger cars emitted only 4 5 % due to their small share in the total passenger fleet and availability of emission controls. Assuming that the share of superemitters is 105 % in the on-road diesel fleet, we estimate that these high-emitting vehicles are responsible for 4330 % of all BC emissions from on-road vehicles. Under this assumption, the role of superemitters in emissions by vehicle type varies from about 40 % for trucks and buses to 40 % for cars and 48 % for LCVs. This reflects the fact that the truck fleet is much older than the fleet of diesel passenger cars.

We also estimate BC emissions from off-road diesel sources including diesel locomotives, ships, off-road engines in industry, construction and agriculture, and from diesel generators. We estimate that off-road diesel sources emitted 287.57 Gg of BC and 6.75 Gg of OC in Russia in 2014. Stationary engines in industry are the largest source of off-road BC emissions followed by locomotives, agriculture, and diesel generators. Off-road diesel sources emitted 578 % of all diesel BC emissions. Off-road superemitters emitted 4321% of emissions from off-road diesel sources. These results do not include emissions from military diesel usage. Military vehicles can be a large source of BC emissions given that they use high-sulfur diesel.

The total emissions from diesel sources in Russia are estimated to be 489.2 Gg of BC and 17.25.9 Gg of OC in 2014.

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Table 1. $PM_{2.5}$ emission factors and BC/PM ratios for off-road diesel sources.

Sector	Emission controls	$PM_{2.5}$, g kg^{-1}	Source	$BC/PM_{2.5}$ ratio	Source
Diesel generators	No control	6.0	Bond et al. (2004)	0.66	Bond et al. (2004)
Heat plants	No control	0.25	Bond et al. (2004)	0.29	Bond et al. (2004)
Industry (stationary engines)	No control	4.308	EEA (2013), 1.A.4.,Table 3-2	0.55	EEA (2013), 1.A.4.,Table D3
	1991-Stage I	3.551	EEA (2013), 1.A.4.,Table 3-2	0.55	EEA (2013), 1.A.4.,Table D3
	Stage II	1.031	EEA (2013), 1.A.4.,Table 3-2	0.80	EEA (2013), 1.A.4.,Table D3
Construction	No control	4.308	EEA (2013), 1.A.4.,Table 3-2	0.55	EEA (2013), 1.A.4.,Table D3
	1991-Stage I	3.551	EEA (2013), 1.A.4.,Table 3-2	0.55	EEA (2013), 1.A.4.,Table D3
Rail	No control	4.62	Yan et al. (2014)	0.65	EEA (2013), 1.A.3.c.,Table A.1
Ships	No control	1.4	EEA (2013), 1.A.3.d.,Table 3-2	0.31	EEA (2013) 1.A.3.d., Table 3-2
Agriculture	No control	3.755	EEA (2013), 1.A.4.c.ii, Table 3-2	0.55	EEA (2013), 1.A.4.c ii, Table D3
	1991-Stage I	1.644	EEA (2013), 1.A.4.c ii, Table 3-2	0.54	EEA (2013), 1.A.4.c ii, Table D3
	Stage I	0.832	EEA (2013), 1.A.4.c ii, Table 3-2	0.79	EEA (2013), 1.A.4.c ii, Table D3
	Stage II	0.627	EEA (2013), 1.A.4.c ii, Table 3-2	0.77	EEA (2013), 1.A.4.c ii, Table D3

Table 2. Diesel consumption by sector in 2014 (kt).

Diesel consumption	2013	2014
Domestic supply	**30 350**	**31 991**
Transformation processes	1211	1349
Electricity plants	945	1034
Heat plants	266	315
Energy industry own use (coal, oil, gas)	173	236
Final consumption	**28 966**	**30 406**
Industry	2785	3279
Mining	1281	1509
Other industry	1504	1771
Construction	438	414
Transport	23 993	24 970
Rail	2337	2261
Road	21 066	22 189
Domestic navigation	423	372
Other transport	167	148
Agriculture and fishing	1749	1711
Agriculture	1592	1557
Fishing	157	154
Other	31	32

Source: (CENEf, 2016)

Table 3. Percentage of active diesel and gasoline vehicles.

	Share of all active vehicles (Avtostat)	Share of active diesel vehicles (calculated)	Share of active gasoline vehicles (calculated)
Cars	76 %	86 %	75 %
LCVs	80 %	84 %	67 %
Trucks	49 %	57 %	41 %
Buses	64 %	70 %	63 %

Table 4. BC emissions from active on-road diesel vehicles in 2014, (Gg).

	Cars	LCVs	Trucks	Buses	Total
Euro 0	0.1	0.7	3.5	0.3	4.6
Euro 1	0.0	0.3	0.3	0.1	0.8
Euro 2	0.1	0.4	1.2	0.3	2.0
Euro 3	0.1	0.5	1.6	0.4	2.7
Euro 4	0.2	1.0	0.4	0.0	1.6
Euro 5	0.0	0.0	0.1	0.0	0.1
Total Euro 0-5	0.6	2.8	7.2	1.1	11.8
Superemitters	0.5	2.7	5.1	0.7	8.9
TOTAL	1.1	5.5	12.3	1.8	20.7

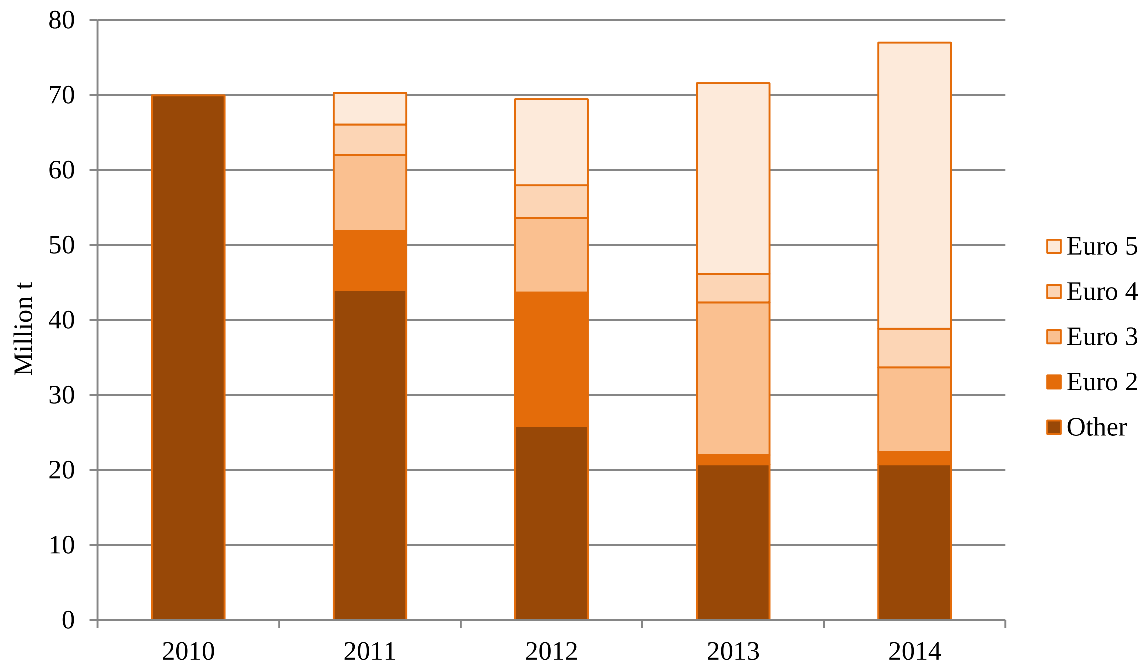
Table 5. BC and OC emissions in Russia in 2014 (Gg).

Sector	BC	OC
On-road vehicles	20.7	10.5
Rail	8.4	1.7
Other industry	5.3	1.1
Mining	4.4	1.3
Agriculture	4.2	1.2
Diesel generators	4.1	0.8
Construction	1.2	0.4
Ships	0.5	0.1
Other sectors	0.4	0.1
Total	49.2	17.2

Table 6. The results of BC emission studies for Russia.

Study	Base year	Emission source categories	BC emissions (Gg)
Bond et al. (2004)	1996	Agricultural burning, industry, open fire, power generation, residential biofuels, road-transport, off-road transport	200
Lamarque et al. (2010)	2000	Residential/domestic sources, forest fires, industry, diesel engines	360
		Diesel transport (including aircrafts and marine shipping)	32
IIASA ECLIPSE dataset (Sand et al., 2016)	2010	All anthropogenic emissions (domestic, energy/industrial/waste, transport , agricultural fires, gas flaring)	182
		Transport	52
Huang et al. (2015)	2010	Flaring, residential, transport, industry, and power plants	224
		On-road transport	45
Russia's National Report to the Arctic Council (MNRE,2015)	2013	All anthropogenic emissions (agriculture, industry, transport, services)	359
		Transport	8 Gg
Donchenko (2006)	2006	On-road transport	54 Gg PM (29 Gg BC)*
Donchenko (2013)	2011	On-road transport	39 Gg PM (20 Gg BC)*
Evans et al. (2015)	2010	All diesel sources	46
		On-road diesel transport	20
This study	2014	All diesel sources	49
		On-road diesel transport	21

* - Assuming that BC/PM speciation ratio for on-road transport is 0.53 (EEA, 2013)



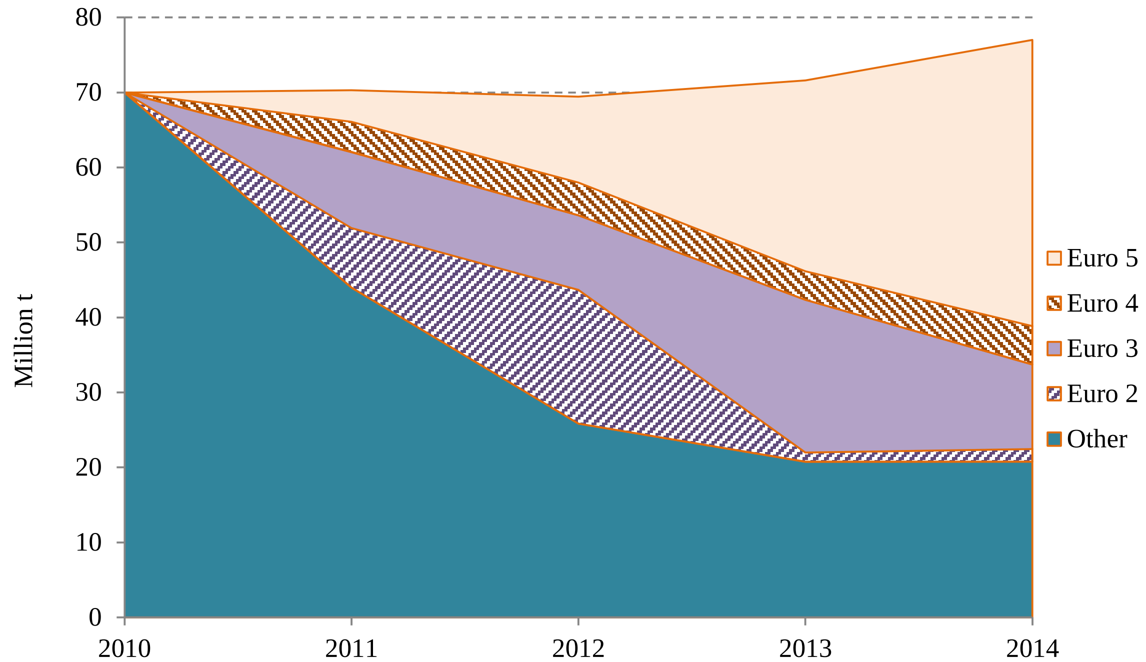


Figure 1. Production of diesel fuel by Euro class in Russia, 2010-2014, Mt.

Source: (Fedstat, 2015e).

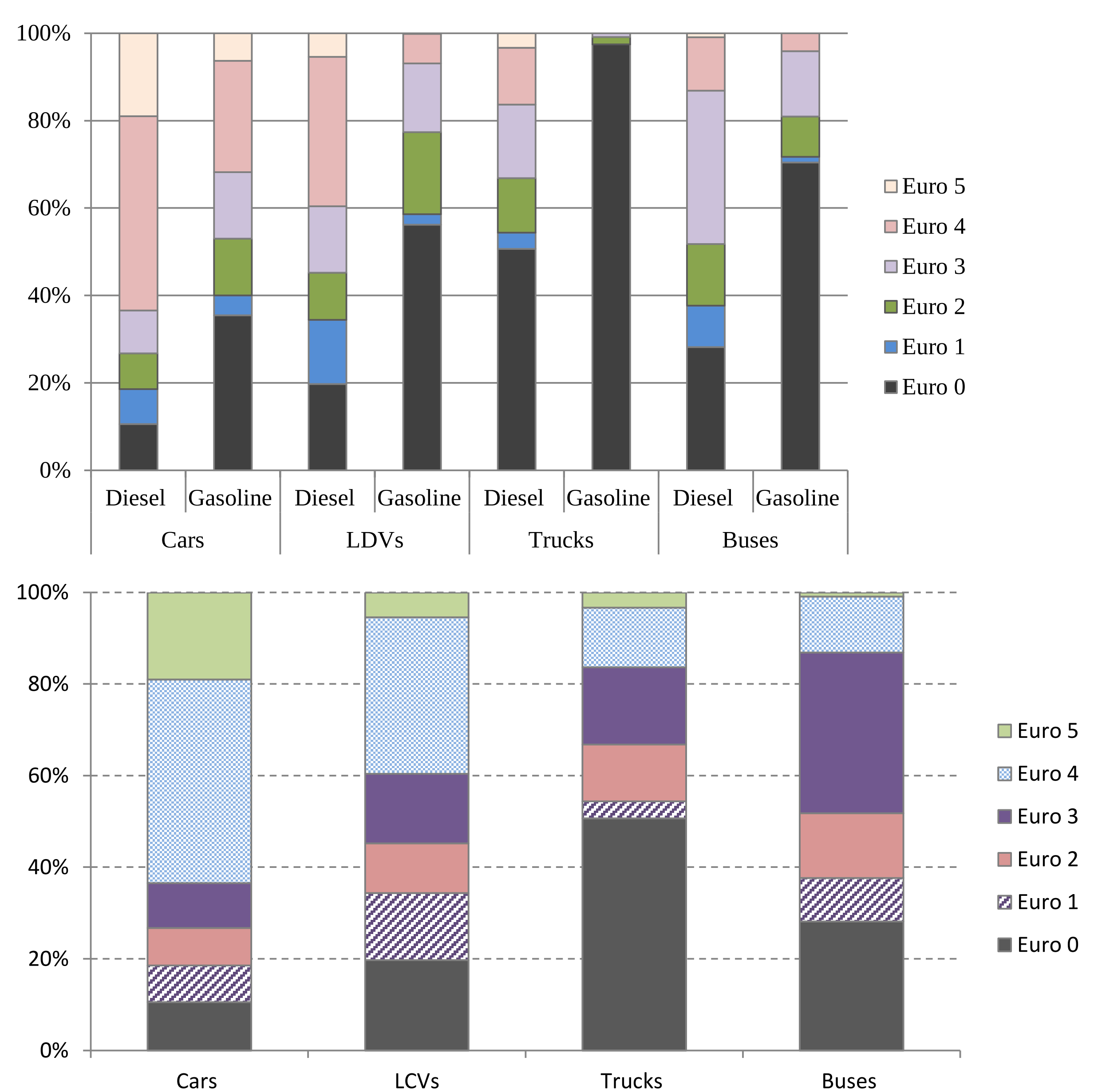


Figure 2. The distribution of diesel ~~and gasoline~~ vehicles by emission standard.

Source: (Avtostat, 2015c).

Table S1. Emission standards for on-road vehicles in the EU and Russia.

Passenger cars*	Introduced in the EU	Introduced in Russia	Heavy-duty diesel engines	Introduced in the EU	Introduced in Russia
Euro 1	1992	-	Euro I	1992	-
Euro 2	1996	2006	Euro II	1996	2006
Euro 3	2000	2008	Euro III	2000	2008
Euro 4	2005	2013	Euro IV	2005	2013
Euro 5	2009	2014	Euro V	2008	2016
Euro 6	2014	n/a	Euro VI	2013	n/a

* By convention, light-duty vehicles are marked with Arabic numerals while Roman numbers are used for heavy-duty vehicles (trucks and buses).

Table S2. COPERT and NIIAT emission factors and BC speciation for hot operation stage.

Type	Subcategory	COPERT EF, g/km			Blended NIIAT EFs, g/km			EC/PM*	OC/EC*
Cars		Urban	Rural	Highway	Urban	Rural	Highway		
Euro 0		0.271	0.199	0.146	0.250	0.150	0.170	0.55	0.70
Euro 1		0.07	0.057	0.087	0.073	0.040	0.050	0.70	0.40
Euro 2		0.058	0.047	0.045	0.073	0.040	0.050	0.80	0.23
Euro 3		0.035	0.029	0.038	0.053	0.030	0.030	0.85	0.15
Euro 4		0.034	0.029	0.025	0.016	0.090	0.090	0.87	0.13
Euro 5		0.003	0.002	0.002	0.004	0.002	0.002	0.20	2.00
LCV									
Euro 0		0.281	0.285	0.337	0.290	0.210	0.230	0.55	0.70
Euro 1		0.099	0.07	0.118	0.087	0.060	0.100	0.70	0.40
Euro 2		0.099	0.07	0.118	0.087	0.060	0.100	0.80	0.23
Euro 3		0.066	0.047	0.079	0.057	0.040	0.060	0.85	0.15
Euro 4		0.035	0.024	0.041	0.033	0.020	0.030	0.87	0.13
Euro 5		0.002	0.001	0.001	0.002	0.001	0.002	0.20	2.00
Trucks									
Euro 0	<=7,5 t	0.4	0.297	0.211	0.543	0.180	0.180	0.50	0.80
Euro I	<=7,5 t	0.157	0.116	0.09	0.360	0.140	0.140	0.65	0.40
Euro II	<=7,5 t	0.069	0.056	0.064	0.220	0.080	0.080	0.65	0.40
Euro III	<=7,5 t	0.082	0.061	0.04	0.153	0.060	0.060	0.70	0.30
Euro IV	<=7,5 t	0.017	0.014	0.015	0.030	0.010	0.010	0.75	0.25
Euro V	<=7,5 t	0.021	0.018	0.015	0.030	0.010	0.010	0.75	0.25
Euro 0	7,5 - 12 t	0.423	0.301	0.201	0.893	0.400	0.400	0.50	0.80
Euro I	7,5 - 12 t	0.262	0.182	0.129	0.640	0.330	0.330	0.65	0.40
Euro II	7,5 - 12 t	0.115	0.087	0.098	0.230	0.100	0.100	0.65	0.40
Euro III	7,5 - 12 t	0.133	0.095	0.062	0.153	0.060	0.060	0.70	0.30
Euro IV	7,5 - 12 t	0.027	0.021	0.02	0.030	0.010	0.010	0.75	0.25
Euro V	7,5 - 12 t	0.034	0.026	0.021	0.030	0.010	0.010	0.75	0.25

Euro 0	12 - 14 t	0.452	0.32	0.232	1.073	0.550	0.550	0.50	0.80
Euro I	12 - 14 t	0.28	0.199	0.147	0.697	0.480	0.480	0.65	0.40
Euro II	12 - 14 t	0.128	0.095	0.109	0.310	0.180	0.180	0.65	0.40
Euro III	12 - 14 t	0.141	0.099	0.071	0.193	0.130	0.130	0.70	0.30
Euro IV	12 - 14 t	0.03	0.023	0.02	0.040	0.020	0.020	0.75	0.25
Euro V	12 - 14 t	0.036	0.028	0.023	0.040	0.020	0.020	0.75	0.25
Euro 0	> 14 t	0.625	0.439	0.29	1.073	0.550	0.550	0.50	0.80
Euro I	> 14 t	0.386	0.271	0.175	0.697	0.480	0.480	0.65	0.40
Euro II	> 14 t	0.164	0.118	0.129	0.310	0.180	0.180	0.65	0.40
Euro III	> 14 t	0.199	0.139	0.087	0.193	0.130	0.130	0.70	0.30
Euro IV	> 14 t	0.039	0.029	0.023	0.040	0.020	0.020	0.75	0.25
Euro V	> 14 t	0.049	0.037	0.028	0.040	0.020	0.020	0.75	0.25
Buses									
Euro 0	<=15 t	0.858	0.574	0.388	0.880	0.270	0.295	0.50	0.80
Euro I	<=15 t	0.294	0.221	0.173	0.650	0.215	0.230	0.65	0.40
Euro II	<=15 t	0.142	0.114	0.107	0.398	0.195	0.175	0.65	0.40
Euro III	<=15 t	0.146	0.11	0.099	0.197	0.105	0.100	0.70	0.30
Euro IV	<=15 t	0.035	0.027	0.022	0.040	0.025	0.025	0.75	0.25
Euro V	<=15 t	0.042	0.031	0.038	0.037	0.025	0.025	0.75	0.25
Euro 0	15 - 18 t	0.767	0.52	0.312	1.523	0.430	0.500	0.50	0.80
Euro I	15 - 18 t	0.412	0.294	0.217	0.890	0.310	0.400	0.65	0.40
Euro II	15 - 18 t	0.197	0.157	0.138	0.680	0.310	0.270	0.65	0.40
Euro III	15 - 18 t	0.195	0.148	0.108	0.250	0.130	0.120	0.70	0.30
Euro IV	15 - 18 t	0.049	0.037	0.027	0.050	0.030	0.030	0.75	0.25
Euro V	15 - 18 t	0.055	0.042	0.036	0.050	0.030	0.030	0.75	0.25
Euro 0	>18 t	0.957	0.675	0.395	1.523	0.430	0.500	0.50	0.80
Euro I	>18 t	0.517	0.37	0.227	0.757	0.310	0.400	0.65	0.40
Euro II	>18 t	0.265	0.212	0.174	0.583	0.310	0.270	0.65	0.40
Euro III	>18 t	0.24	0.17	0.125	0.250	0.130	0.120	0.70	0.30
Euro IV	>18 t	0.06	0.045	0.029	0.050	0.030	0.030	0.75	0.25
Euro V	>18 t	0.066	0.049	0.04	0.050	0.030	0.030	0.75	0.25

Sources: (Emisia, 2015;NIIAT, 2012).

* EC/PM and OC/EC speciation factors are derived from the COPERT model.

Table S3. Number of active diesel vehicles by type and emission standard in Russia, 2014.

	Cars	LCVs	Trucks	Buses
Euro 0	100 620	150 345	470 737	24 994
Euro 1	103 529	119 732	43 093	10 038
Euro 2	113 576	94 135	173 337	17 541
Euro 3	144 298	140 923	293 520	49 725
Euro 4	691 199	353 189	271 189	19 481
Euro 5	329 941*	58 703	77 404	1 615
Total	1 483 163	917 027	1 329 280	123 394

* - includes 2110 Euro 6 cars

Calculated based on (Avtostat, 2015).

Table S4. The annual average distance traveled by type of vehicles, thousand kmyr^{-1}.

	Cars	LCVs	Trucks	Buses
NIIAT (1998)	15 10 for 5-year old Russian cars 10 for 10-year old foreign cars		35 in cities 60 suburban 100 intercity	Russian: 50 in cities 65 suburban 80 intercity Foreign: 60 in cities 80 suburban 105 intercity
NIIAT (2008)	14-16 owned by individuals 25-30 owned by companies		30-40	40-50
Avtostat (2010)	16.7 15.3 Russian 18 foreign-made	55	63	65
ICCT (2015)	10	10	13-38	56

Table S5. Average number kilometers traveled by type of vehicles.

Vehicle type	Subsector	Emission standard	Annual kilometers traveled
Passenger Cars	Diesel 1,4 - 2,0 l	Conventional	10 000
	Diesel 1,4 - 2,0 l	PC Euro 1 - 91/441/EEC	10 000
	Diesel 1,4 - 2,0 l	PC Euro 2 - 94/12/EEC	15 000
	Diesel 1,4 - 2,0 l	PC Euro 3 - 98/69/EC Stage2000	15 000
	Diesel 1,4 - 2,0 l	PC Euro 4 - 98/69/EC Stage2005	18 000

	Diesel 1,4 - 2,0 l	PC Euro 5 - EC 715/2007	20 000
Light Commercial Vehicles	Diesel <3,5 t	Conventional	37 000
	Diesel <3,5 t	LD Euro 1 - 93/59/EEC	37 000
	Diesel <3,5 t	LD Euro 2 - 96/69/EEC	55 000
	Diesel <3,5 t	LD Euro 3 - 98/69/EC Stage2000	55 000
	Diesel <3,5 t	LD Euro 4 - 98/69/EC Stage2005	66 000
	Diesel <3,5 t	LD Euro 5 - 2008 Standards	73 000
Heavy Duty Trucks	Rigid <=7,5 t	Conventional	42 000
	Rigid <=7,5 t	HD Euro I - 91/542/EEC Stage I	42 000
	Rigid <=7,5 t	HD Euro II - 91/542/EEC Stage II	63 000
	Rigid <=7,5 t	HD Euro III - 2000 Standards	63 000
	Rigid <=7,5 t	HD Euro IV - 2005 Standards	75 000
	Rigid <=7,5 t	HD Euro V - 2008 Standards	84 000
	Rigid 7,5 - 12 t	Conventional	42 000
	Rigid 7,5 - 12 t	HD Euro I - 91/542/EEC Stage I	42 000
	Rigid 7,5 - 12 t	HD Euro II - 91/542/EEC Stage II	63 000
	Rigid 7,5 - 12 t	HD Euro III - 2000 Standards	63 000
	Rigid 7,5 - 12 t	HD Euro IV - 2005 Standards	75 000
	Rigid 7,5 - 12 t	HD Euro V - 2008 Standards	84 000
	Rigid 12 - 14 t	Conventional	42 000
	Rigid 12 - 14 t	HD Euro I - 91/542/EEC Stage I	42 000
	Rigid 12 - 14 t	HD Euro II - 91/542/EEC Stage II	63 000
	Rigid 12 - 14 t	HD Euro III - 2000 Standards	63 000
	Rigid 12 - 14 t	HD Euro IV - 2005 Standards	75 000
	Rigid 12 - 14 t	HD Euro V - 2008 Standards	84 000
	Rigid 14 - 20 t	Conventional	42 000
	Rigid 14 - 20 t	HD Euro I - 91/542/EEC Stage I	42 000
	Rigid 14 - 20 t	HD Euro II - 91/542/EEC Stage II	63 000
	Rigid 14 - 20 t	HD Euro III - 2000 Standards	63 000
	Rigid 14 - 20 t	HD Euro IV - 2005 Standards	75 000
	Rigid 14 - 20 t	HD Euro V - 2008 Standards	84 000
Buses	Urban Buses Midi <=15 t	Conventional	43 000
	Urban Buses Midi <=15 t	HD Euro I - 91/542/EEC Stage I	43 000
	Urban Buses Midi <=15 t	HD Euro II - 91/542/EEC Stage II	65 000
	Urban Buses Midi <=15 t	HD Euro III - 2000 Standards	65 000
	Urban Buses Midi <=15 t	HD Euro IV - 2005 Standards	78 000
	Urban Buses Midi <=15 t	HD Euro V - 2008 Standards	87 000
	Urban Buses Standard 15 - 18 t	Conventional	43 000
	Urban Buses Standard 15 - 18 t	HD Euro I - 91/542/EEC Stage I	43 000
	Urban Buses Standard 15 - 18 t	HD Euro II - 91/542/EEC Stage II	65 000
	Urban Buses Standard 15 - 18 t	HD Euro III - 2000 Standards	65 000
	Urban Buses Standard 15 - 18 t	HD Euro IV - 2005 Standards	78 000

Urban Buses Standard 15 - 18 t	HD Euro V - 2008 Standards	87 000
Urban Buses Articulated >18 t	Conventional	43 000
Urban Buses Articulated >18 t	HD Euro I - 91/542/EEC Stage I	43 000
Urban Buses Articulated >18 t	HD Euro II - 91/542/EEC Stage II	65 000
Urban Buses Articulated >18 t	HD Euro III - 2000 Standards	65 000
Urban Buses Articulated >18 t	HD Euro IV - 2005 Standards	78 000
Urban Buses Articulated >18 t	HD Euro V - 2008 Standards	87 000

Results of emission calculations

The COPERT 4 model with NIIAT emission factors. The assumptions on average annual kilometers traveled remain the same.

Table S6. OC emissions from the adjusted diesel fleet with superemitters (Gg).

	Cars	LCVs	Trucks	Buses	Total
Euro 0	0.07	0.47	2.83	0.20	3.58
Euro 1	0.02	0.11	0.14	0.05	0.31
Euro 2	0.03	0.10	0.49	0.10	0.72
Euro 3	0.02	0.08	0.49	0.12	0.70
Euro 4	0.03	0.13	0.09	0.01	0.26
Euro 5	0.01	0.01	0.03	0.00	0.05
Total	0.18	0.88	4.07	0.48	5.62

Table S7. BC emissions, assuming that all registered trucks and buses use diesel fuel (Gg).

	Trucks	Buses	Total
Euro 0	33.2	3.8	80.2
Euro 1	1.1	0.3	3.6
Euro 2	2.5	0.8	13.6
Euro 3	2.3	0.8	11.4
Euro 4	0.4	0.1	5.8
Euro 5	0.1	0.0	0.2
Total	39.7	5.7	114.8

Table S8. BC emissions from all registered diesel vehicles (Gg).

	Cars	LCVs	Trucks	Buses	Total
Euro 0	0.36	1.85	15.39	0.66	18.26
Euro 1	0.10	0.54	1.06	0.20	1.91
Euro 2	0.18	0.68	2.33	0.32	3.51
Euro 3	0.16	0.66	2.27	0.42	3.52
Euro 4	0.27	1.03	0.42	0.04	1.77
Euro 5	0.01	0.00	0.12	0.00	0.13
Total	1.08	4.77	21.58	1.66	29.09

Table S9. BC emissions from the adjusted diesel fleet without accounting for superemitters (Gg).

	Cars	LCVs	Trucks	Buses	Total
Euro 0	0.20	1.30	6.16	0.46	8.11
Euro 1	0.08	0.41	0.53	0.16	1.18
Euro 2	0.14	0.54	1.40	0.29	2.37
Euro 3	0.14	0.56	1.71	0.42	2.82
Euro 4	0.24	0.98	0.38	0.05	1.65
Euro 5	0.01	0.00	0.12	0.00	0.13
Total	0.80	3.79	10.28	1.39	16.26

Table S10. Uncertainty estimates for BC and OC emissions from on-road vehicles.

	Central	Minimum	Maximum
Share of superemitters	15%	10%	20%
Annual distance traveled, km	Avtostat	NIIAT	Avtostat
Cars	15 000	15 000	15 000
LCVs	55 000	30 000	55 000
Trucks	63 000	45 000	63 000
Buses	65 000	50 000	65 000
PM emissions factor	COPERT	COPERT -20%	COPERT +20%
BC/PM speciation ratio	COPERT	COPERT -10%	COPERT +10%
Emissions, Gg			
BC normal	11.8	7.1	12.3
BC superemitters	8.9	3.4	15.7
BC total	**20.7**	**10.5**	**28.0**
OC normal	5.6	4.3	5.0
OC superemitters	4.9	2.1	8.7
OC total	**10.5**	**6.4**	**13.7**

References

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