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APPLYING THE HANDPRINT APPROACH TO ASSESS THE AIR POLLUTANT REDUCTION POTENTIAL OF PARAFFINIC RENEWABLE DIESEL FUEL IN THE CAR FLEET OF THE CITY OF HELSINKI

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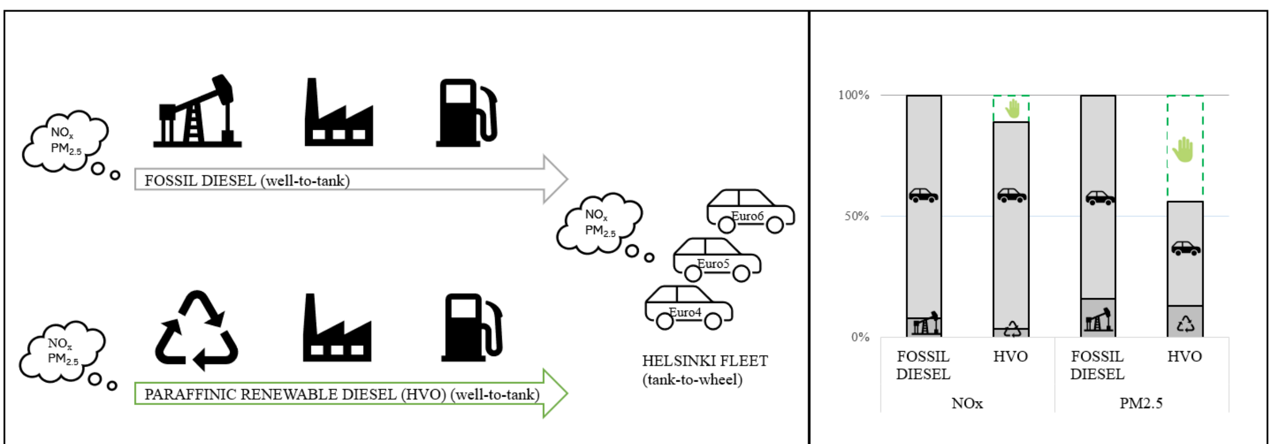
ABSTRACT

Ambient air pollution is a global environmental challenge, especially in densely populated regions. In urban areas, road traffic is an important source of fine particulate matter ($PM_{2.5}$) and nitrogen oxide (NO_x) emissions, primarily due to exhaust gases. The adoption of paraffinic renewable diesel fuels for urban transportation has been suggested as a more sustainable and less air polluting alternative to conventional fossil fuels. The aim of this study is, therefore, to examine whether the transition from the conventional fossil fuel diesel to paraffinic renewable diesel (hydrotreated vegetable oil [HVO] according to the EN 15940 standard) can reduce $PM_{2.5}$ and NO_x emissions in an urban environment. The life cycle assessment-based handprint approach is utilized to calculate and demonstrate the emissions reduction. The reduction potential is quantified for Euro 4, 5 and 6 passenger diesel cars using actual car fleet, mileage, local temperature, and laboratory emissions measurements for 2018 in Helsinki, Finland. Our study shows that the use of HVO can reduce $PM_{2.5}$ and NO_x emissions in urban areas. According to our results, $PM_{2.5}$ emissions could be reduced by 49% for the defined location and car fleet by replacing conventional fossil-fuel diesel with HVO. In the case of NO_x emissions, the local reduction potential is 7%. Overall life cycle emissions reduction potentials of NO_x and $PM_{2.5}$ emissions are 11% and 44%, respectively, if conventional diesel is replaced by HVO. Thus, the manufacturer of HVO can communicate the air quality handprint, and in particular, the NO_x and $PM_{2.5}$ handprints, that their product can achieve.

Keywords: air pollution, hydrotreated vegetable oil, HVO, nitrogen oxide, fine particulate matter, air quality handprint

Graphical abstract



Life cycle NO_x and $PM_{2.5}$ emissions of conventional fossil diesel and HVO in Helsinki.

1. Introduction

Outdoor air pollution is a significant environmental health risk that is estimated to have caused approximately 4.2 million premature deaths worldwide in 2016 (WHO, 2018). Air pollutants increase cases of respiratory, vascular and heart diseases and have adverse effects on ecosystems and the climate (EEA, 2018a). Air pollution is closely related to global climate change because the combustion of fossil fuels is the main anthropogenic source of greenhouse gases, airborne particulate matter, sulphur and nitrogen oxides, and short-lived air pollutants such as black carbon and methane (Landrigan et al., 2018; Perera, 2017; Scovronick et al., 2015). Ambient (outdoor) air pollutants are typically particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) (WHO, 2018).

The adverse health impacts of poor air quality are concentrated in urban areas, which are not only population centres but also emissions hotspots, primarily due to traffic emissions. The main air pollutant compounds in cities that adversely affect human health are fine particulate matter and nitrogen oxides (NO_x) (EEA, 2019). Fine particulate matter with a diameter of 2.5 microns or less (≤ $PM_{2.5}$) has been recognized as having the most significant effect on human health as it can penetrate the lung barrier and enter the blood system (Anderson et al., 2012; Hänninen et al., 2014; WHO, 2018). Additionally, $PM_{2.5}$ emissions include various substances harmful to human health, such as heavy metals (Mazziotti-Tagliani et al., 2017; Soleimani et al., 2018), carbon compounds (Park and Lee, 2015) and sulphurs and carcinogens (WHO, 2003). Nitrogen oxides (NO_x) comprise nitric oxide (NO) and nitrogen dioxide (NO_2) (EEA, 2019). At high concentrations and under long-term exposure, NO_2 can cause inflammation of the airways, reduced lung function and other respiratory symptoms (WHO, 2003). Nitrogen oxides also have detrimental effects on environment, such as ozone layer depletion and acidification when dissolved in water bodies (Boningari and Smirniotis, 2016; Sepehri et al., 2020)

Road traffic is the biggest source of NO_x in EU-28 countries, and it was responsible for 39% of all NO_x emissions in 2017 (EEA, 2019). NO_x emissions from road vehicles are problematic since they are released near ground level, often in densely populated areas where the number of exposed citizens is high. The transportation sector is also an important contributor to fine particulate emissions, although sources of $PM_{2.5}$ emissions vary considerably depending on location, geographical characteristics and meteorological conditions (Vallius, 2005; WHO, 2018). $PM_{2.5}$ emissions from road traffic derive from exhaust gases but also from non-exhaust sources, such as brake wear, road wear, tyre wear and road dust resuspension (Amato et al., 2014). In European cities, road transport is assumed to be responsible for around 12% of primary fine particulate matter emissions (EEA, 2018b), and in OECD countries the proportion can be much higher (OECD, 2020). Nevertheless, emissions from vehicle exhausts have decreased significantly in recent years due to tightened emission legislations (EEA, 2019). At the EU level, this includes stricter emission standards (e.g. Euro 1-6) (EC, 2018, 2007) and the imposition of requirements for fuel quality (EC, 2009). However, the overall emissions from the transport sector have decreased less than expected because of the increase in passenger and freight volumes (EEA, 2018b). Furthermore, NO_x emissions under real driving conditions, particularly from diesel-powered passenger cars and vans, have shown to be higher in many cases than is permitted under European (Euro) emission regulations (EEA, 2018b; Kadijk et al., 2016). One explanation for this is that previously used test cycles did not represent real driving practices; hence, more accurate test cycles have since been developed and adopted for emissions measurement (Degraeuwe and Weiss, 2017).

As well as being responsible for a substantial amount of greenhouse gas emissions, diesel-powered vehicles have traditionally been significant sources of both NO_x and $PM_{2.5}$ emissions (Prasad and Bella, 2010; Reşitoılu et al., 2015). As an alternative to conventional fossil-fuel diesel, bio-based diesel has shown to offer advantages in terms of greenhouse gas and pollutant emissions (Naik et al., 2010). It is assumed that due to the properties of biofuel, the combustion process in the engine produces less air pollutant compounds than the combustion of conventional diesel and may thus reduce local air pollution. However, the characteristics and amount of air pollutant emissions from bio-based diesel vary depending on the composition of the fuel and the source of the raw materials (Lapuerta et al., 2008; Suarez-Bertoa et al., 2019). Bio-based diesel can be produced, for example, from different types of vegetable oils, used cooking oils and animal fats (Dimitriadis et al., 2018). The combustion of first-generation biodiesels produced from esterified vegetable oils (FAME) showed a reduction in particulate matter, hydrocarbon and carbon monoxide emissions but an increase in NO_x emissions compared to conventional diesel (Giakoumis et al., 2012; Hoekman and Robbins, 2012; Hutter et al., 2015; Torregrosa et al., 2013; Wu et al., 2009).

More advanced biofuels, such as hydrotreated vegetable oil (HVO), Fischer-Tropsch (FT) diesel and dimethylether (DME), were developed to offer a more sustainable alternative to first-generation biodiesels. The usage of HVO has been shown to result in reduced particulate matter, hydrocarbon and carbon monoxide emissions compared to conventional diesel (Happonen et al., 2013; Kuronen et al., 2007; Pflaum et al., 2010; Pirjola et al., 2019; Sugiyama et al., 2012). Reductions in particulate matter and carbon monoxide emissions are mainly due to the high cetane number and zero aromatics of HVO (Pflaum et al., 2010; Sugiyama et al., 2012). Research results concerning NO_x emissions from HVO combustion are not consistent and unequivocal since NO_x emissions vary for different types of engine technology, fuel properties, test cycles, type of fuel injection system and other engine parameters (Aatola et al., 2009; Erkkilä et al., 2011; Pechout et al., 2019). Some studies have observed NO_x reductions for HVO compared to conventional diesel (Aatola et al., 2009; Bohl et al., 2018; Hemanandh and Narayanan, 2017; Ogunkoya et al., 2015; Pechout et al., 2019; Pflaum et al., 2010), whereas other studies have shown comparable or increased NO_x emissions from HVO combustion (Dimitriadis et al., 2018; Happonen et al., 2013; Kousoulidou et al., 2014; Millo et al., 2015; Sugiyama et al., 2012). Regarding carbon dioxide emissions, HVO has shown to have lower global warming potential (GWP100) when taking the whole life cycle into account (Arvidsson et al., 2011; Grönman et al., 2019) as well as lower tailpipe carbon dioxide emissions (Nylund et al., 2011).

Although numerous studies have examined air pollutant emissions from different bio-based and fossil fuels, there is still a lack of understanding of how the transition from fossil fuels to renewables would affect emissions and air quality in cities. The potential for a reduction in $PM_{2.5}$ and NO_x emissions when transitioning to renewable diesel is usually studied based on laboratory emissions measurements, and transition effects in a real operating environment are often neglected. To our knowledge, only a few studies have assessed the change in the emission levels at the urban scale when bio-based diesel fuel is used instead of conventional diesel (Dias et al., 2019; Hutter et al., 2015; Pino-Cortés et al., 2015; Ribeiro et al., 2016). Furthermore, these studies focused on FAME and not HVO.

Hence, this paper aims to identify and quantify whether using HVO in passenger diesel cars can reduce NO_x and $PM_{2.5}$ exhaust gas emissions in an urban Nordic city (Helsinki, Finland), and if so, by how much. In the study, we combine the laboratory measurement of emissions data with local car fleet, vehicle mileage, and weather observations. Life cycle NO_x and $PM_{2.5}$ emissions are also taken into account to observe possible trade-offs in emissions between life cycle stages. Previous studies have mainly concentrated on tank-to-wheel emissions since their impact on local air quality has been recognized to be the most significant. In this work, however, we also include well-to-tank life cycle analysis. One aspect of the novelty of this article is that our study combines emissions from Euro 4, 5 and 6 diesel passenger cars operating under different ambient temperatures because previous studies have shown a clear temperature-dependency for vehicle emissions (Grange et al., 2019; Ko et al., 2019; Suarez-Bertoa and Astorga, 2018). Laboratory measurements on emissions are conducted using the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) (EC, 2017; EU, 2017), which more closely resembles real driving conditions – and hence, emissions – than the previously used New European Driving Cycle (NEDC) (Degraeuwe and Weiss, 2017).

The research presented in this paper adopts the guidelines for handprint thinking presented by Grönman et al. (2019) and Pajula et al. (2018). The handprint approach offers guidance on how to set up a comparison between a novel solution and the business-as-usual situation. This allows the change, or preferably the reduction, in emissions to be seen when the new solution is introduced in the same operating environment as the baseline solution. The handprint approach is based on the standardized life cycle assessment (LCA) method and was originally developed to quantify the greenhouse gas reduction potential of products when used by a customer; this is the first attempt to utilize the handprint guidelines in an outdoor air quality setting.

2. Methods

The carbon handprint assessment approach for a product is structured on a framework with step-by-step guidance (Pajula et al., 2018), which is slightly modified here for the assessment of air quality changes. These modifications to the original carbon handprint approach are presented in yellow in Figure 1. The right-hand side in the same figure outlines the paraffinic renewable diesel case examined in this study using the modified handprint approach for air quality.

	Renewable diesel made of used cooking oil (hydrotreated vegetable oil, HVO)
Identify customer of the product	City of Helsinki, Finland
Identify relevant indicators	NO_x and particulate emissions $PM_{2.5}$ throughout the life cycle of the fuel
Identify potential air quality handprint contributors	Reduction of NO_x and particulate emissions $PM_{2.5}$ due cleaner combustion
Define the baseline	Fossil reference diesel in average vehicle used throughout the year 2018 (between centigrade 23 & -7) in defined fleet
Define the functional unit	Kilometres driven with the defined fleet in Helsinki in year 2018
Define the system boundaries	Well-to-tank + tank-to-wheel
Define data needs and sources	Primary data of the fuel production processes, complemented with secondary data from GaBi database. Measured data on use phase emissions from laboratory tests (from year 2018). Mileage of the different euro classes for the year 2018 in Helsinki (data from the city of Helsinki). Share of the euro classes 4, 5 and 6 in the certain fleet (data from Traficom). Mean temperatures of every month in Helsinki in 2018 (data from Finnish Meteorological Institute).
Calculate the air quality footprints	Total release of NO_x and $PM_{2.5}$ over the examined system boundary for both handprint and the baseline solution
Calculate the air quality handprint	Difference between NO_x and $PM_{2.5}$ emissions in baseline and handprint solution
Critical review of the air quality handprint	Critical review through manuscript review process
Communicate the results	Communicate the results respecting appropriateness, clarity, credibility, and transparency
	Emission reduction of NO_x and $PM_{2.5}$ Communication units (for NO_x & $PM_{2.5}$) scaled to local mileage: Local change in emissions with certain mileage and fleet in a specific region.

Figure 1. Framework for the air quality handprint approach using the case study of replacing conventional diesel with paraffinic renewable diesel in passenger cars in Helsinki in 2018.

The fuel examined here is HVO made from used cooking oil. HVO is a paraffinic renewable diesel fuel with zero aromatics and meets the requirements of the EN 15940 standard. The city of Helsinki, Finland, was assumed to be the customer in this case, meaning the assessment examined how a change of diesel fuel would affect the amounts of selected air pollutants in the

Helsinki region. The examination covered the entire year of 2018, which was the most recent year for which representative data were available. The handprint approach, when applied to air quality, requires an additional step to identify the relevant indicators, in this case, airborne pollutants. This paper investigates $PM_{2.5}$ and NO_x emissions because they have been identified as important contributors to ambient air quality in cities (Martínez-Bravo and Martínez-del-Río, 2020). Additionally, traffic exhaust emissions, especially from diesel-powered vehicles, are a major source of these compounds in urban areas (EEA, 2019; Karagulian et al., 2015; Prasad and Bella, 2010). Moreover, $PM_{2.5}$ has been identified as being very harmful to human health, and NO_x also adversely impacts on health (Anderson et al., 2012; Hänninen et al., 2014; WHO, 2003). Sulphur oxide and ground-level ozone were excluded from the study as, as in most of Europe, legislation in Finland sets limits on the sulphur content of road fuels. Hence, SO_x emissions from road traffic have declined markedly since the early 1990s and SO_x levels in Finland are well below the limit set to protect human health (Finnish Environment Institute, 2015; IEA, 2016). Ground-level ozone was excluded because it is formed in photochemical reactions involving volatile organic compounds and NO_x and does not itself occur in emissions (Zhang et al., 2019).

The hypothesis for creating an air quality handprint is that the transition from conventional fossil fuel diesel to HVO decreases NO_x and $PM_{2.5}$ emissions due to the cleaner combustion process in the vehicle's engine. In this study, the 100% conventional diesel used in Helsinki was substituted with 100% HVO. Thus, conventional diesel serves as the baseline product in this case. The baseline diesel contained 7% biocomponents, in this case FAME, which is in line with current European fuel standards that allow up to 7% biodiesel volume in fossil fuel diesel (EN 590:2013, 2017). The replacement of conventional diesel was studied for a defined fleet representing diesel-powered passenger cars from three different Euro regulation tiers (Euro 4, 5 and 6). Euro 4 regulations came into effect in 2005, Euro 5 in 2009 and Euro 6 in 2014 (DieselNet, 2020).

In 2018, the total vehicle mileage in the Helsinki city area was 2 463 million kilometres. The calculated share of passenger vehicles was 1 645 million kilometres and the share of diesel passenger vehicles was 420 million kilometres. Euro 4, 5 and 6 diesel-powered passenger cars corresponded to 26% of all passenger vehicles and 17% of all vehicles in Helsinki. The proportions of Euro 4, 5 and 6 of all diesel passenger vehicles in Helsinki were 17%, 35% and 42%, respectively. (Figure 2)

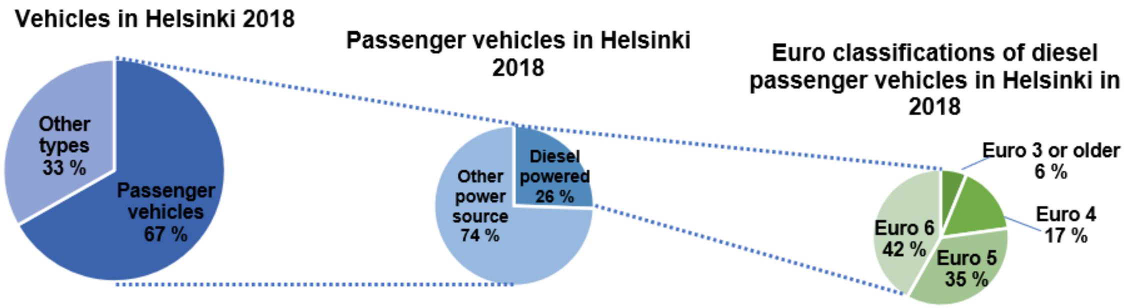


Figure 2. Examined vehicles in Helsinki in 2018.

The functional unit used in the study was kilometres driven by the defined diesel-powered passenger vehicle fleet in the Helsinki city area in the year 2018. A more detailed depiction of the vehicle fleet is presented in Table 1.

	Diesel passenger vehicles					Other passenger vehicles	All passenger vehicles
	Euro 4	Euro 5	Euro 6*	Other Euro classes	In total	In total	
Number of passenger vehicles	8 341	17 744	20 961	3 068	50 114	146 110	196 224
Million kilometres	69.74	148.73	175.62	26.05	420.13	1 224.87	1 645.00

*Includes both Euro 6 and Euro 6dTemp class diesel passenger cars.

Table 1. Number of passenger vehicles and driven kilometres in Helsinki in 2018.

The examination included the entire well-to-wheel life cycle of the studied fuels. However, the results are presented separately for the production phase (well-to-tank) and use phase (tank-to-wheel) as those emissions occur in different geographical locations (Figure 3). Use phase covers exhaust emissions that are emitted during the drive.

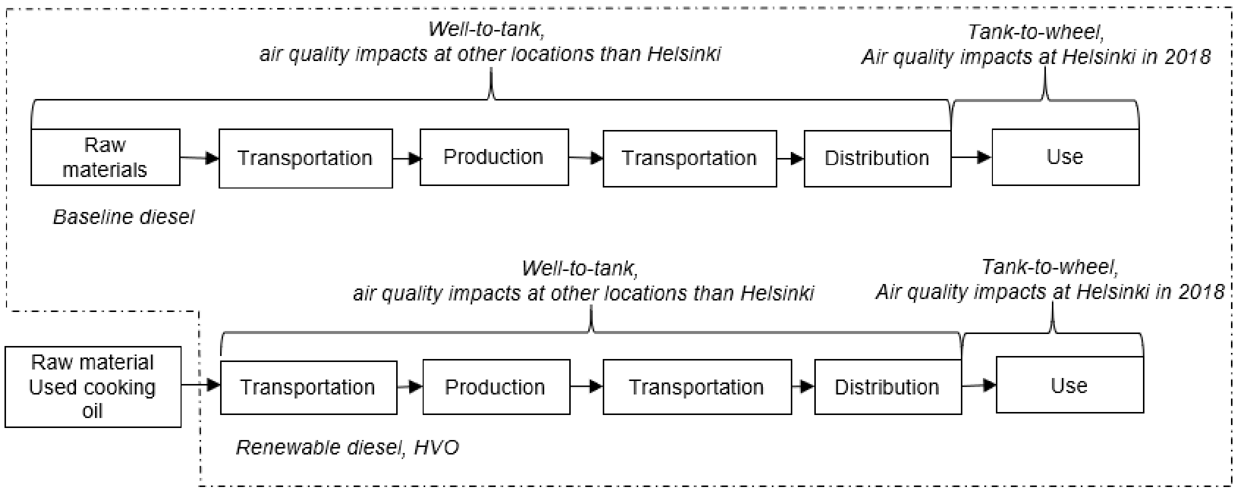


Figure 3. System boundaries.

The well-to-tank emissions of the renewable diesel were derived from the manufacturer; in the case of conventional diesel, the LCA modelling software GaBi's database was used (Sphera, 2019). The tank-to-wheel emissions of the conventional and renewable diesel were quantified under laboratory conditions using the WLTC test cycle at -7℃ and 23℃. Emissions occurring between these temperatures were estimated via interpolation. The impacts of temperature on the formation of NO_x and $PM_{2.5}$ were taken into account using the mean temperatures of each month in 2018, taken from the Finnish Meteorological Institute's (Finnish Meteorological Institute, 2018) Kaisaniemi measurement point in Helsinki. Based on the average temperatures, the coldest month in Helsinki in 2018 was February, where the average temperature was -7℃, and the warmest was July, with the average of 21.1℃. The consumption of diesel fuel was assessed based on the data considering the actual mileage during the year 2018 (Helsingin kaupunki, 2018). Mileage was assumed to be shared evenly across each month of the year. The number of diesel cars and the proportions of Euro 4, 5 and 6 vehicles in the study area were based on vehicle data from the Finnish Transport and Communications Agency (Traficom, 2019).

The subsequent steps in the framework required the calculation of the air pollutant emissions both for the renewable diesel and for the baseline diesel. Any reduction in air pollutants using renewable diesel would result in an air quality handprint – in this case specifically NO_x and $PM_{2.5}$ handprints. The results and the appropriate way to communicate them are presented in the following section.

3. Results

The NO_x and $PM_{2.5}$ exhaust emissions in Helsinki based on the year 2018 fleet are presented in Figure 4. The NO_x exhaust emissions for conventional and HVO diesel were 283 000 kg and 264 400 kg, respectively. The annual $PM_{2.5}$ exhaust emissions in Helsinki were 3 000 kg for conventional diesel and 1 600 kg for HVO. Figure 4 also shows how the emissions in the studied fleet were distributed among the included Euro regulated car groups. In the defined Helsinki

2018 fleet, Euro 5 cars were responsible for 66% of conventional diesel and 65% of HVO NO_x exhaust emissions. When considering $PM_{2.5}$ exhaust emissions, the share of Euro 4 cars was 94% and 89% for conventional diesel and HVO, respectively.

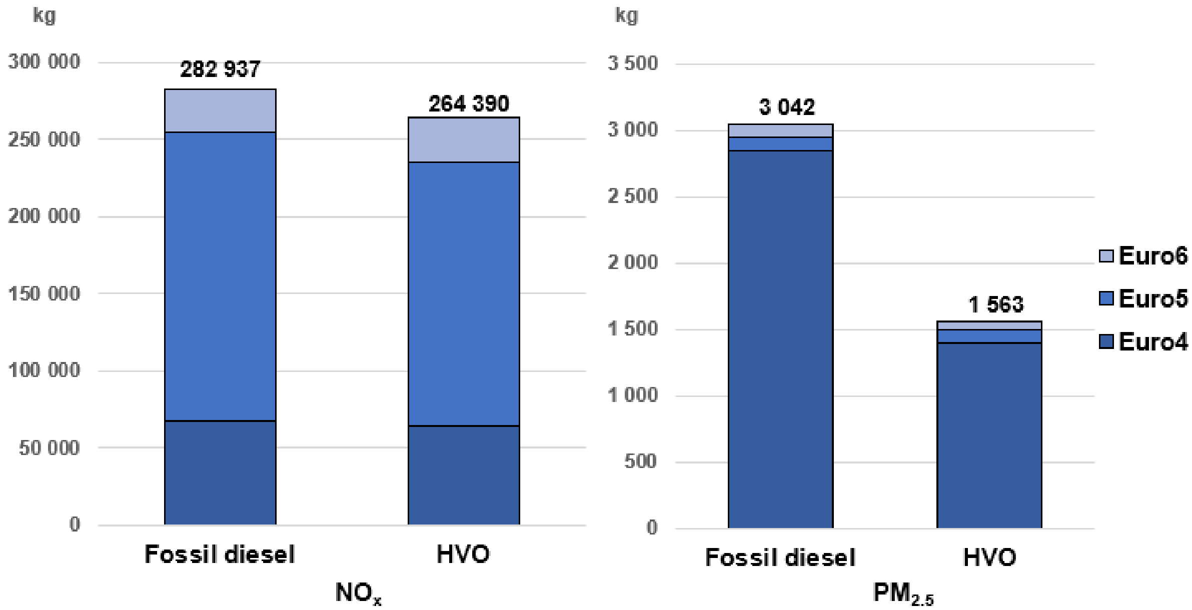


Figure 4. Annual NO_x and $PM_{2.5}$ exhaust emissions in Helsinki based on 2018 values.

The reduction potentials of NO_x and $PM_{2.5}$ exhaust emissions due to the replacement of conventional diesel with HVO in Helsinki based on 2018 values in the studied fleet are presented in Figure 5. The reduction potential is highest for $PM_{2.5}$ emissions, which are reduced on average by 49% when compared to conventional diesel. In the case of NO_x emissions, the reduction potential is 7%. However, when communicated in kilograms, the NO_x reduction potential in Helsinki based on the year 2018 fleet proved to be highest, at 18 500 kg, and the $PM_{2.5}$ exhaust emissions reduction potential is 1 500 kg. In the Helsinki 2018 fleet, the highest NO_x reduction potential is for Euro 5 cars, at 9%, and in the case of $PM_{2.5}$ exhaust emissions, for Euro 4 cars, at 50%.

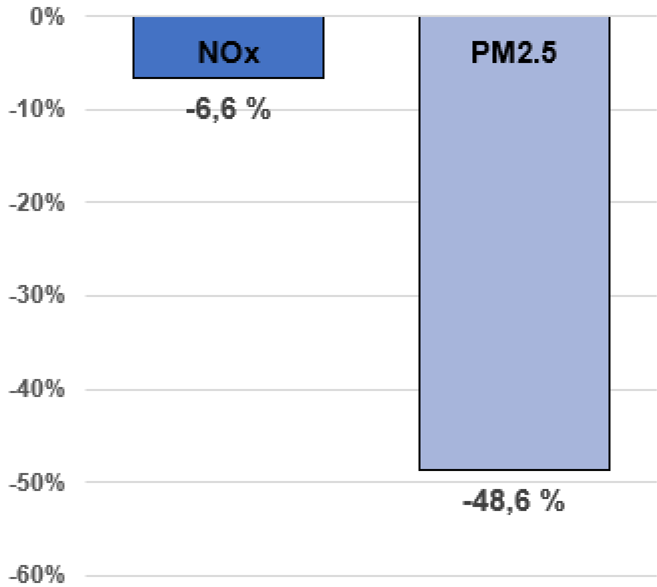


Figure 5. Annual reduction potential of NO_x and $PM_{2.5}$ exhaust emissions in Helsinki based on the year 2018 values for diesel-powered passenger cars.

In this study, local NO_x and $PM_{2.5}$ exhaust emissions in Helsinki represent the tank-to-wheel phase of the studied fuels' life cycles. However, in the handprint methodology, it is important to examine the whole life cycle to identify the most emission-producing life cycle stages and examine possible trade-offs. Hereby, it should be noted that the well-to-wheel and tank-to-wheel emissions occur at different geographical locations. Local air quality impacts can only be identified through a separate calculation of the different life cycle stages. Figure 6 shows the contribution of well-to-tank and tank-to-wheel phases to the total life cycle NO_x and $PM_{2.5}$ emissions of the studied fuels. The results show that the tank-to-wheel phase dominates in every studied case. When considering NO_x life cycle emissions, the tank-to-wheel phase covers 92% of conventional fuel and 96% of HVO life cycle emissions. In the case of $PM_{2.5}$ emissions, tank-to-wheel emissions account for 84% of life cycle emissions in conventional diesel and 77% in HVO.

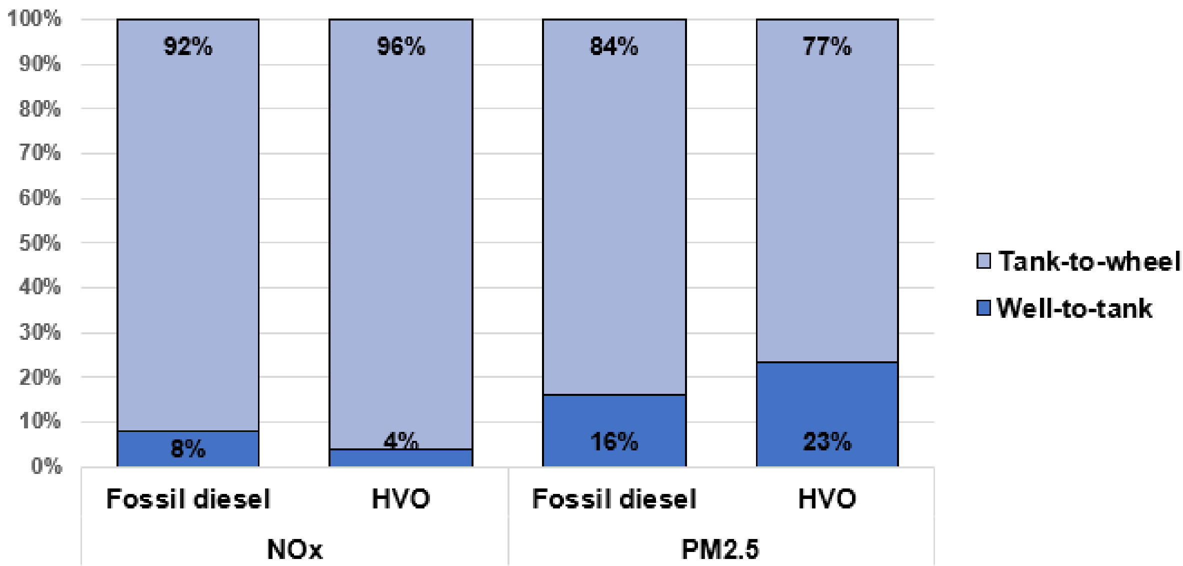


Figure 6. Share of the different life cycle phases of NO_x and $PM_{2.5}$ emissions.

As mentioned previously, the total life cycle reduction potential of NO_x and $PM_{2.5}$ emissions can be considered as the air quality handprint. The emissions reduction, i.e. the NO_x and $PM_{2.5}$ handprint, can be calculated by comparing the well-to-wheel NO_x and $PM_{2.5}$ emissions of the studied fuels. Figure 7 demonstrates the total life cycle NO_x and $PM_{2.5}$ emissions of the studied fuels based on the fuel consumption of the Helsinki 2018 fleet. The results show that NO_x emissions are 32 700 kg lower when HVO is used instead of conventional diesel. Similarly, $PM_{2.5}$ emissions are 1 580 kg lower with HVO. As a consequence, the emissions reduction could be considered as a handprint, which means that a manufacturer of the HVO could communicate the handprint of 32 700 kg, or 11%, for NO_x in this case with the studied fleet as they have enabled an equivalent footprint reduction of the customer. The $PM_{2.5}$ handprint would be 1 580 kg, or 44%, for the defined fleet in Helsinki in 2018.

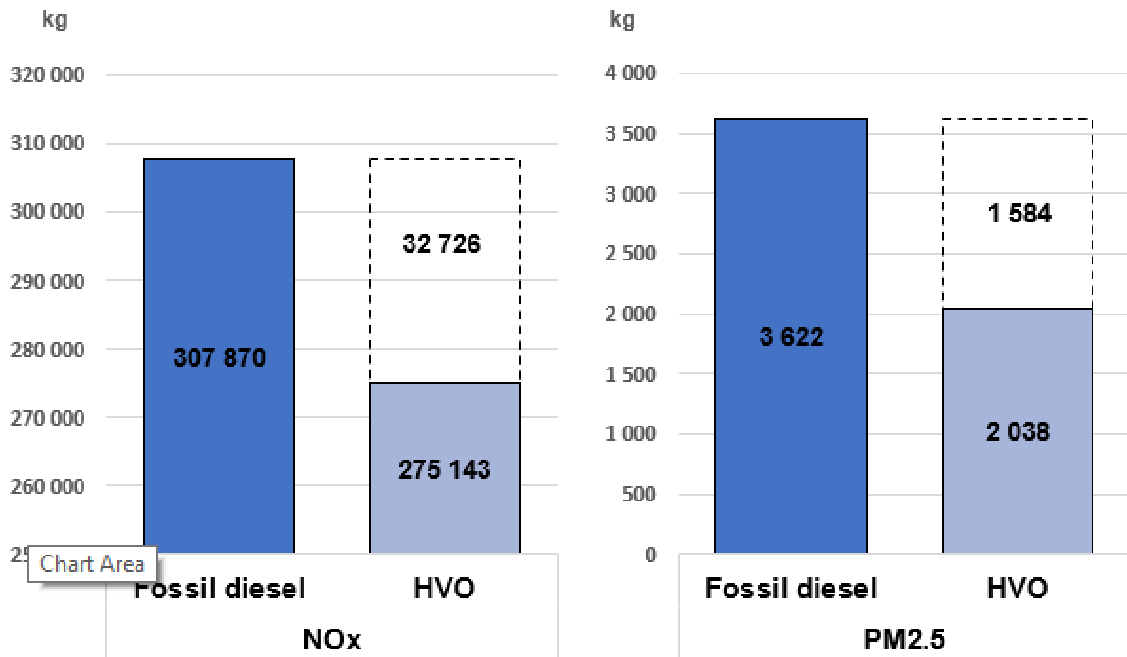


Figure 7. Total life cycle NO_x and $PM_{2.5}$ emissions of the studied fuels and their NO_x and $PM_{2.5}$ handprints.

4. Discussion

The results show that paraffinic renewable diesel has the potential to reduce NO_x and $PM_{2.5}$ emissions in a city such as Helsinki with its average fleet and climatic conditions. The paraffinic renewable diesel fuel may offer a way to decrease $PM_{2.5}$ emissions, especially from older cars without advanced emissions cleaning technologies; hence, the biggest emissions reduction can be achieved in areas where the car fleet is relatively old. Our findings are in line with previous studies, which have shown a reduction in $PM_{2.5}$ emissions for paraffinic renewable diesel combustion compared to conventional fossil-fuel diesel (Bortel et al., 2019; Nylund et al., 2011; Pflaum et al., 2010; Sugiyama et al., 2012). $PM_{2.5}$ emissions were 49% lower in the case of paraffinic renewable diesel compared to conventional diesel when observing the use-phase emissions. According to our results, the reduction potential for $PM_{2.5}$ emissions is higher for Euro 4 diesel passenger cars than newer cars. The reason for the improvement in the particulate emissions reduction rate originates from the introduction of diesel particulate filters (DPF) in Euro 5 diesel passenger cars (EC, 2007). While many previous studies (Dias et al., 2019; Hutter et al., 2015; Kousoulidou et al., 2014) proved that the use of first-generation biodiesel will increase the NO_x emissions of transportation, our results highlight that NO_x emissions may also decrease through the use of paraffinic renewable diesel instead of conventional fossil-fuel diesel. NO_x emissions in the use phase are tightly linked to the outside temperature and vehicle model, and consequently, it is important to examine NO_x emissions with the actual car fleet and climatic conditions in a certain location. The NO_x emissions reduction corresponds to the NO_x emissions produced by 40.9 million kilometres driven with conventional diesel when calculated with the average emissions from Euro 4-6 diesel passenger cars at an ambient air temperature of 7°C, which was the annual average temperature in Helsinki in 2018. For Euro 4 specifically, the $PM_{2.5}$ reduction is similar to the $PM_{2.5}$ emissions caused by 113.1 million kilometres driven with conventional diesel.

Our results do not include emissions from Euro 0-3 passenger diesel cars. The share of Euro 0-3 diesel cars in the studied fleet was 6.5% and if all the vehicles in the study area were included, the results may change. Additionally, according to scientific evidence, NO_x reductions are higher in heavy-duty than in light-duty diesel vehicles when using HVO as a fuel instead of conventional diesel (Aatola et al., 2009; Bohl et al., 2018; Neste, 2016). This is mainly due to differences between engine sizes and engine properties, especially higher cycles and loads in heavy-duty engines (Muncrief, 2016; Neste, 2020). Heavy duty vehicles cause greater amount of NO_x emissions due to higher temperatures in the engine. However, ignition and combustion properties of HVO result in a smaller share of premixed combustion, thus causing less NO_x emissions (Neste, 2020). Heavy traffic was excluded from our study because no recent laboratory emissions measurements were available. Including Euro 0-3 passenger vehicles and heavy traffic to the calculation would offer a better understanding of diesel cars' air pollutant impacts on local air quality and would also help to examine the whole potential to reduce local air pollution through fuel replacement. It is also important to conduct the study in areas besides Helsinki because local emissions and conditions along with the local vehicle fleet affect the air pollutant reduction potential. In addition, laboratory measurement data for temperatures below -7°C would be interesting to study because particularly use phase NO_x emissions increase when ambient temperature decreases (Grange et al., 2019; Suarez-Bertoa and Astorga, 2018). Also, further measurements with different vehicles, including heavy traffic, different velocities, and stop-and-go driving, would provide important data.

As the tank-to-wheel phase proved to be the most significant emission source of $PM_{2.5}$ and NO_x, the choice of fuel may have an impact on local air quality. Nevertheless, it is essential to recognize in which locations the emissions from different life cycle stages occur. Further studies are required to put the results into the context of local air pollutant concentrations or to proportion the results to air quality limits. Using dispersion models of air pollutants is necessary to recognize different emission sources affecting local air quality, as is taking weather conditions and other relevant factors into account. Influencing local emissions has traditionally been beyond the reach of individual citizens, but the choice of fuel may give an opportunity to enhance local air quality. In addition to decreased air pollutant emissions, paraffinic renewable diesel has been claimed to have other advantages over conventional diesel. For instance, it has been shown to have lower life cycle and use-phase greenhouse gas emissions than conventional fossil-fuel diesel (Arvidsson et al., 2011; Grönman et al., 2019; Nylund et al., 2011).

Replacing conventional diesel with renewable diesel may bring about positive environmental impacts if NO_x and $PM_{2.5}$ exhaust gas emissions are decreased. Our results highlight that the emissions reduction potential is significant in the tank-to-wheel phase when considering the whole life cycle of the fuels. According to Grönman et al. (2019) and Pajula et al. (2018), a handprint refers to the beneficial environmental impacts of a product when used by a customer. Thus, the well-to-wheel emissions reduction potential could be interpreted as the handprint of the renewable diesel fuel. However, the different life cycle stages must also be studied separately since emissions occur at different geographical locations, meaning it is not appropriate to observe only the total well-to-wheel emissions. Our results show that the handprint approach can also be applied to environmental impacts other than greenhouse gas reduction, and only a slight modification to the approach allowed the specifics of air quality handprint assessment to be tackled. These modifications were identifying the relevant indicators in terms of air pollutants and communicating the results taking into account the locality of emission release.

5. Conclusions

The need to improve urban air quality has led to the search for solutions to reduce traffic-related emissions. On the other hand, the initiators of these solutions require a sound, science-based method with which to calculate and communicate the benefits their product offers in reducing pollution. This study presents the results of how a paraffinic renewable diesel can reduce the annual NO_x and $PM_{2.5}$ emissions in the Helsinki area. The handprint calculation approach is implemented in the scope of outdoor air quality.

Based on the concluded air quality handprint assessment, wherein the lifetime emissions of a paraffinic renewable diesel (HVO) are compared to those of baseline conventional diesel, the results give a strong indication that by choosing the paraffinic renewable diesel, the NO_x and $PM_{2.5}$ emissions can be significantly reduced, especially in the use phase of the fuel. The emissions reduction potential is noteworthy, especially in older diesel vehicles with no novel filtration or other emissions reduction system. Using HVO-based renewable diesel in Euro 4 (or older) vehicles can reduce $PM_{2.5}$ emissions in particular. Also, NO_x reduction is possible and indeed significant when considering absolute NO_x kilograms. Accordingly, manufacturers of paraffinic renewable diesel can communicate that if all the Euro 4-6 diesel vehicles in Helsinki were to shift to their paraffinic renewable diesel, they would gain an annual NO_x handprint of 32 700 kg and a $PM_{2.5}$ handprint of 1600 kg based on Helsinki year 2018 data.

Despite the findings on the reduction potential of NO_x and $PM_{2.5}$ demonstrated here, the effect is less significant for modern diesel vehicles. As car fleets are updated, the benefit of using renewable diesel instead of fossil diesel diminishes in terms of air quality. This indicates that the best results for improving air quality can be achieved when using paraffinic renewable diesel in areas where the fleet uses older technology. However, using paraffinic renewable diesel instead of conventional diesel also decreases the burden on exhaust gas cleaning systems in newer cars while reducing the overall air pollutant emissions of the car fleet.

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References

Aatola, H., Larmi, M., Sarjovaara, T., Mikkonen, S., 2009. Hydrotreated vegetable Oil (HVO) as a renewable diesel fuel: Trade-off between NOx, particulate emission, and fuel consumption of a heavy duty engine. SAE Int. J. Engines 1, 1251–1262.

Amato, F., Cassee, F.R., Denier, H.A.C., Gon, V. Der, Gehrig, R., Gustafsson, M., Hafner, W., Harrison, R.M., Jozwicka, M., Kelly, F.J., Moreno, T., Prevot, A.S.H., Schaap, M., Sunyer, J., Querol, X., 2014. Urban air quality : The challenge of traffic non-exhaust emissions. J. Hazard. Mater. 275, 31–36.

Anderson, J.O., Thundiyil, J.G., Stolbach, A., 2012. Clearing the Air: A Review of the Effects of Particulate Matter Air Pollution on Human Health. J. Med. Toxicol. 8, 166–175.

Arvidsson, R., Persson, S., Fröling, M., Svanström, M., 2011. Life cycle assessment of hydrotreated vegetable oil from rape, oil palm and Jatropha. J. Clean. Prod. 19, 129–137.

Bohl, T., Smallbone, A., Tian, G., Roskilly, A.P., 2018. Particulate number and NOx trade-off comparisons between HVO and mineral diesel in HD applications. Fuel 215, 90–101.

Boningari, T., Smirniotis, P.G., 2016. Impact of nitrogen oxides on the environment and human health: Mn-based materials for the NOx abatement. Curr. Opin. Chem. Eng. 13, 133–141.

Bortel, I., Vávra, J., Takáts, M., 2019. Effect of HVO fuel mixtures on emissions and performance of a passenger car size diesel engine. Renew. Energy 140, 680–691.

Degraeuwe, B., Weiss, M., 2017. Does the New European Driving Cycle (NEDC) really fail to capture the NOX emissions of diesel cars in Europe? Environ. Pollut. 222, 234–241.

Dias, D., Antunes, A.P., Tchepel, O., 2019. Modelling of emissions and energy use from biofuel fuelled vehicles at urban scale. Sustain. 11, 2902.

DieselNet, 2020. Emission standards [WWW Document]. URL https://dieselnet.com/standards/eu/ld.php (accessed 3.24.20).

Dimitriadis, A., Natsios, I., Dimaratos, A., Katsaounis, D., Samaras, Z., Bezergianni, S., Lehto, K., 2018. Evaluation of a Hydrotreated Vegetable Oil (HVO) and Effects on Emissions of a Passenger Car Diesel Engine. Front. Mech. Eng. 4, 1–19.

EC, 2007. Regulation (EC) no 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and mai, Official journal of the European Union.

EC, 2009. European Parliament Directive 2009/30/EC, Official Journal of the European Union.

EC, 2017. Commission Regulation (EU) 2017/1154 of 7 June 2017 amending Regulation (EU) 2017/1151 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenge.

EC, 2018. Consolidated text: Commission Regulation (EC) No 692/2008 of 18 July 2008 implementing and amending Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger.

EEA, 2018a. Air quality in Europe — 2018 report, Report.

EEA, 2018b. Emissions of air pollutants from transport. Eur. Environ. Agency 12.

EEA, 2019. Air quality in Europe — 2019 report — EEA Report No 10/2019.

EN 590:2013, 2017. Automotive fuels. Diesel. Requirements and test methods.

Erkkilä, K., Nylund, N.O., Hulkkonen, T., Tilli, A., Mikkonen, S., Saikkonen, P., Mäkinen, R., Amberla, A., 2011. Emission performance of paraffinic HVO diesel fuel in heavy duty vehicles. In: SAE Technical Papers.

EU, 2017. Commission Regulation (EU) 2017/1151 of 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 a.

Finnish Environment Institute, 2015. Emission reduction targets met for sulphur and nitrogen oxides – but not for ammonia [WWW Document]. URL https://www.ymparisto.fi/en-US/Maps_and_statistics/The_state_of_the_environment_indicators/Air_pollutants/Emission_reduction_targets_met_for_sulph(28713)

Finnish Meteorological Institute, 2018. Download observations. [WWW Document]. URL https://en.ilmatieteenlaitos.fi/download-observations

Giakoumis, E.G., Rakopoulos, C.D., Dimaratos, A.M., Rakopoulos, D.C., 2012. Exhaust emissions of diesel engines operating under transient conditions with biodiesel fuel blends. Prog. Energy Combust. Sci. 38, 691–715.

Grange, S.K., Farren, N.J., Vaughan, A.R., Rose, R.A., Carslaw, D.C., 2019. Strong Temperature Dependence for Light-Duty Diesel Vehicle NOx Emissions. Environ. Sci. Technol. 53, 6587–6596.

Grönman, K., Pajula, T., Sillman, J., Leino, M., Vatanen, S., Kasurinen, H., Soininen, A., Soukka, R., 2019. Carbon handprint – An approach to assess the positive climate impacts of products demonstrated via renewable diesel case. J. Clean. Prod. 206, 1059–1072.

Hänninen, O., Knol, A.B., Jantunen, M., Lim, T.A., Conrad, A., Rappolder, M., Carrer, P., Fanetti, A.C., Kim, R., Buekers, J., Torfs, R., Iavarone, I., Classen, T., Hornberg, C., Mekel, O.C.L., 2014. Environmental burden of disease in Europe: Assessing nine risk factors in six countries. Environ. Health Perspect. 122, 439–446.

Happonen, M., Heikkilä, J., Aakko-Saksa, P., Murtonen, T., Lehto, K., Rostedt, A., Sarjovaara, T., Larmi, M., Keskinen, J., Virtanen, A., 2013. Diesel exhaust emissions and particle hygroscopicity with HVO fuel-oxygenate blend. Fuel 103, 380–386.

Helsingin kaupunki, 2018. Tilastotietoja Helsingin autoliikenteestä [WWW Document]. URL https://www.hel.fi/helsinki/fi/kartat-ja-liikenne/kadut-ja-liikennesuunnittelu/tutkimus-ja-tilastot/moottoriajoneuvoliikenteen-maarat/

Hemanandh, J., Narayanan, K. V., 2017. Production of Green Diesel by Hydrotreatment Using Jatropha Oil: Performance and Emission Analysis. Waste and Biomass Valorization 8, 1931–1939.

Hoekman, S.K., Robbins, C., 2012. Review of the effects of biodiesel on NOx emissions. Fuel Process. Technol. 96, 237–249.

Hutter, H.P., Kundi, M., Moshammer, H., Shelton, J., Krüger, B., Schicker, I., Wallner, P., 2015. Replacing Fossil Diesel by Biodiesel Fuel: Expected Impact on Health. Arch. Environ. Occup. Heal. 70, 4–9.

IEA, 2016. Energy and Air Pollution: World Energy Outlook Special Report, Comprehensive Energy Systems.

Kadijk, G., Ligterink, N., Mensch, P. Van, Smokers, R., 2016. NO x emissions of Euro 5 and Euro 6 diesel passenger cars – test results in the lab and on the road.

Karagulian, F., Belis, C.A., Dora, C.F.C., Prüss-Ustün, A.M., Bonjour, S., Adair-Rohani, H., Amann, M., 2015. Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. Atmos. Environ. 120, 475–483.

Ko, J., Myung, C.L., Park, S., 2019. Impacts of ambient temperature, DPF regeneration, and traffic congestion on NOx emissions from a Euro 6-compliant diesel vehicle equipped with an LNT under real-world driving conditions. Atmos. Environ. 200, 1–14.

Kousoulidou, M., Dimaratos, A., Karvountzis-Kontakiotis, A., Samaras, Z., 2014. Combustion and emissions of a common-rail diesel engine fueled with HWCO. J. Energy Eng. 140.

Kuronen, M., Mikkonen, S., Aakko, P., Murtonen, T., 2007. Hydrotreated Vegetable Oil as Fuel for Heavy Duty Diesel Engines. SAE Tech. Pap. 2007-01-4031.

Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N. (Nil), Baldé, A.B., Bertollini, R., Bose-O'Reilly, S., Boufford, J.I., Breysse, P.N., Chiles, T., Mahidol, C., Coll-Seck, A.M., Cropper, M.L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., Hunter, D., Khare, M., Krupnick, A., Lanphear, B., Lohani, B., Martin, K., Mathiasen, K. V., McTeer, M.A., Murray, C.J.L., Ndahimananjara, J.D., Perera, F., Potočnik, J., Preker, A.S., Ramesh, J., Rockström, J., Salinas, C., Samson, L.D., Sandilya, K., Sly, P.D., Smith, K.R., Steiner, A., Stewart, R.B., Suk, W.A., van Schayck, O.C.P., Yadama, G.N., Yumkella, K., Zhong, M., 2018. The Lancet Commission on pollution and health. Lancet 391, 462–512.

Lapuerta, M., Armas, O., Rodríguez-Fernández, J., 2008. Effect of biodiesel fuels on diesel engine emissions. Prog. Energy Combust. Sci. 34, 198–223.

Martínez-Bravo, M., Martínez-del-Río, J., 2020. Urban Pollution and Emission Reduction. In: Leal Filho, W., Marisa Azul, A., Brandli, L., Gökçin Özuyar, P., Wall, T. (Eds.), Sustainable Cities and Communities. Springer International Publishing, Cham, pp. 905–915.

Mazziotti-Tagliani, S., Carnevale, M., Armiento, G., Montereali, M.R., Nardi, E., Inglessis, M., Sacco, F., Palleschi, S., Rossi, B., Silvestroni, L., Gianfagna, A., 2017. Content , mineral allocation and leaching behavior of heavy metals in. Atmos. Environ. 153, 47–60.

Millo, F., Debnath, B.K., Vlachos, T., Ciaravino, C., Postrioti, L., Buitoni, G., 2015. Effects of different biofuels blends on performance and emissions of an automotive diesel engine. Fuel 159, 614–627.

Muncrief, R., 2016. NO x emissions from heavy-duty and light-duty diesel vehicles in the EU : Comparison of real-world performance and current type-approval requirements, The International Council on Clean Transportation (ICCT). Int. Counc. Clean Transp. Rep. 1–14.

Naik, S.N., Goud, V. V., Rout, P.K., Dalai, A.K., 2010. Production of first and second generation biofuels: A comprehensive review. Renew. Sustain. Energy Rev. 14, 578–597.

Neste, 2016. Neste Renewable Diesel Handbook. Espoo.

Neste 2020. Personal communication, 2020.

Nylund, N.O., Erkkilä, K., Ahtiainen, M., Murtonen, T., Saikkonen, P., Amberla, A., Aatola, H., 2011. Optimized usage of NExBTL renewable diesel fuel OPTIBIO. VTT Tied. - Valt. Tek. Tutkimusk. 1–172.

OECD, 2020. Emissions of air pollutants [WWW Document]. URL https://stats.oecd.org/index.aspx?queryid=72722

Ogunkoya, D., Roberts, W.L., Fang, T., Thapaliya, N., 2015. Investigation of the effects of renewable diesel fuels on engine performance, combustion, and emissions. Fuel 140, 541–554.

Pajula, T., Vatanen, S., Pihkola, H., Grönman, K., Kasurinen, H., Soukka, R., 2018. Carbon Handprint Guide [WWW Document]. URL https://www.vtt.fi/sites/handprint/PublishingImages/Carbon_Handprint_Guide.pdf (accessed 12.11.18).

Park, S.S., Lee, K., 2015. Environmental Science Processes & Impacts. Environ. Sci. Process. Impacts 00, 1–12.

Pechout, M., Kotek, M., Jindra, P., Macoun, D., Hart, J., Vojtisek-Lom, M., 2019. Comparison of hydrogenated vegetable oil and biodiesel effects on combustion, unregulated and regulated gaseous pollutants and DPF regeneration procedure in a Euro6 car. Sci. Total Environ. 696, 133748.

Perera, F.P., 2017. Multiple threats to child health from fossil fuel combustion: Impacts of air pollution and climate change. Environ. Health Perspect. 125, 141–148.

Pflaum, H., Hofmann, P., Geringer, B., Weissel, W., 2010. Potential of Hydrogenated Vegetable Oil (HVO) in a Modern Diesel Engine. SAE Tech. Pap. 2010-32-0081.

Pino-Cortés, E., Díaz-Robles, L.A., Cubillos, F., Fu, J.S., Vergara-Fernández, A., 2015. Sensitivity analysis of biodiesel blends on Benzo[a]pyrene and main emissions using MOVES: A case study in Temuco, Chile. Sci. Total Environ. 537, 352–359.

Pirjola, L., Kuuluvainen, H., Timonen, H., Saarikoski, S., Teinilä, K., Salo, L., Datta, A., Simonen, P., Karjalainen, P., Kulmala, K., Rönkkö, T., 2019. Potential of renewable fuel to reduce diesel exhaust particle emissions. Appl. Energy 254, 113636.

Prasad, R., Bella, V.R., 2010. A review on diesel soot emission, its effect and control. Bull. Chem. React. Eng. Catal. 5, 69–86.

Reşitoılu, I.A., Altinişik, K., Keskin, A., 2015. The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. Clean Technol. Environ. Policy 17, 15–27.

Ribeiro, I., Monteiro, A., Lopes, M., 2016. Potential effects of using biodiesel in road-traffic on air quality over the Porto urban area, Portugal. Atmos. Environ. 125, 78–91.

Scovronick, N., Dora, C., Fletcher, E., Haines, A., Shindell, D., 2015. Reduce short-lived climate pollutants for multiple benefits. Lancet 386, e28–e31.

Sepehri, A., Sarrafzadeh, M.H., Avateffazeli, M., 2020. Interaction between Chlorella vulgaris and nitrifying-enriched activated sludge in the treatment of wastewater with low C/N ratio. J. Clean. Prod. 247, 119164.

Soleimani, M., Amini, N., Sadeghian, B., Wang, D., Fang, L., 2018. ScienceDirect Heavy metals and their source identification in particulate matter (PM 2 . 5) in Isfahan City , Iran. J. Environ. Sci. 72, 166–175.

Sphera, 2019. GaBi Ts - Software-System and Database for the Life Cycle Engineering.

Suarez-Bertoa, R., Astorga, C., 2018. Impact of cold temperature on Euro 6 passenger car emissions. Environ. Pollut. 234, 318–329.

Suarez-Bertoa, R., Kousoulidou, M., Clairotte, M., Giechaskiel, B., Nuottimäki, J., Sarjovaara, T., Lonza, L., 2019. Impact of HVO blends on modern diesel passenger cars emissions during real world operation. Fuel 235, 1427–1435.

Sugiyama, K., Goto, I., Kitano, K., Mogi, K., Honkanen, M., 2012. Effects of Hydrotreated Vegetable Oil (HVO) as Renewable Diesel Fuel on Combustion and Exhaust Emissions in Diesel Engine. SAE Int. J. Fuels Lubr. 5, 205–217.

Torregrosa, A.J., Broatch, A., Plá, B., Mónico, L.F., 2013. Impact of Fischer-Tropsch and biodiesel fuels on trade-offs between pollutant emissions and combustion noise in diesel engines. Biomass and Bioenergy 52, 22–33.

Traficom, 2019. Ajoneuvojen avoin data 5.8 [WWW Document]. URL https://www.traficom.fi/fi/ajankohtaista/avoin-data?toggle=Ajoneuvojen avoin data 5.8

Vallius, M., 2005. Characteristics and Sources of Fine Particulate Matter in Urban Air. Publ. Natl. Public Heal. Inst. A6 / 2005 pp: 81.

WHO, 2003. Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide: Report on a WHO Working Group. Bonn, Ger. 13-15 January 2003.

WHO, 2018. Ambient (outdoor) air pollution [WWW Document]. URL https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (accessed 3.9.20).

Wu, F., Wang, J., Chen, W., Shuai, S., 2009. A study on emission performance of a diesel engine fueled with five typical methyl ester biodiesels. Atmos. Environ. 43, 1481–1485.

Zhang, J.J., Wei, Y., Fang, Z., 2019. Ozone pollution: A major health hazard worldwide. Front. Immunol. 10, 1–10.