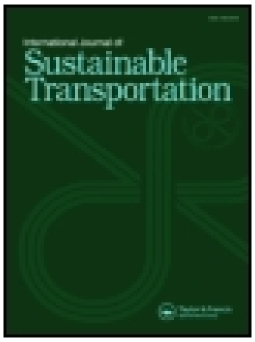

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Sustainable solutions for reducing air-conditioning costs and tailpipe emissions from heavy-duty transportation across Europe

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ABSTRACT
Heavy-duty trucks emit >25% of the CO_2 of the European road transport sector despite representing ≈2.5% of its fleet. Escalating temperatures associated to global warming will increase the use of air-conditioning (AC) in heavy-duty trucks, further raising their fuel consumption and emissions. Thus, sustainable solutions are needed to reduce the thermal loads affecting the truck cabins, to minimize the need for AC and decrease the sector's costs and environmental footprint. We assessed the economic and environmental impact of AC use in the European heavy-duty transportation fleet, for realistic environmental conditions throughout the year, across the different European regions. Potential reductions were estimated for various changes in the optical properties of the cabin external paints and glazing elements (windshield and side-windows). The use of high-reflectivity paints in the cabin external surfaces and low-transmissivity glazing can reduce fuel costs by ≈€195 million/year across Europe (i.e., ≈0.1% of the total fuel costs of the European heavy-duty fleet), and decrease CO_2 emissions by 1% of the reduction target set for 2025. These potential reductions highlight the importance of engaging with transportation stakeholders (e.g., workers unions, vehicle manufacturers, policymakers, and regulating bodies), to raise awareness about the potential benefits for the European transportation sector and the environment, and to promote the necessary adaptation in the transportation fleets.

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Air-conditioning; fuel consumption; heavy-duty trucks; high-reflectivity paints; low-transmissivity glazing; tailpipe emissions

Introduction

The European transport and storage services sector accounts for about 5% of the EU gross value added, employing around 11.7 million people (European Commission, 2019, p. 19). Road transport alone accounts for 49% of the goods transport activities (European Commission, 2019, p. 19). In this sector, truck drivers, especially those of long-haul services, are exposed for long periods to high temperature and solar radiation during their shifts, which can lead to deterioration of driver performance and increased likelihood of accidents (Liu et al., 2017; Wu et al., 2018). Furthermore, prolonged exposure to high temperatures can lead to heat stress and heat-related illness such as exhaustion and heat stroke (Kjellstrom et al., 2016). Importantly, the severity and incidence of these heat-related problems is expected to markedly increase because of global warming and the associated changes in weather patterns. In particular, the rise in frequency, intensity and duration of heat waves (of which the recent series of consecutive heat waves affecting North America are the latest example, The Guardian, 2021) is therefore a major concern (Guerreiro et al., 2018; Jacob et al., 2014; Lhotka et al., 2018).

To maintain a comfort temperature inside the truck cabins, drivers resort to air-conditioning (AC) systems which increase fuel consumption, increasing costs and tailpipe emissions (V. H. Johnson, 2002; Marshall et al., 2019; Zhang et al., 2016). The latter is detrimental to the environment and feeds a vicious cycle—increasing amounts of pollutants contribute to global warming and more frequent and intense heat waves, which in turn, increases the AC use and the associated tailpipe emissions, repeating the cycle. Heavy-duty trucks alone are responsible for almost 5% of the total CO_2 emissions of Europe, and for more than a quarter of the CO_2 of the entire road transport sector (European Environment Agency, 2016a). In February 2019 a compromise was reached for Europe to reduce the average CO_2 emissions from trucks by 15% in 2025 and by 30% in 2030 (ICCT, 2019).

The transportation sector also represents a significant source of air pollution, especially of particulate matter (PM) and NO_x, which are a major health risk factor worldwide. (European Environment Agency, 2018; ICCT, 2019). For instance, in 2017, particulate matter was associated to 2.9 million premature deaths related to respiratory problems, including lung cancer, respiratory infections and obstructive pulmonary disease (Stanaway et al., 2018). The International

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Council on Clean Transportation (ICCT) reports that, despite the progress made to tighten emissions standards or the decrease in emissions over the years, the health impacts of emissions of the road transportation sector are actually increasing at a global scale (Anenberg et al., 2019). A recent study showed that the health benefits of cutting air pollution are observed within weeks and that interventions that reduce it are cost-effective (Schraufnagel et al., 2019). This reinforces the need to find solutions that can reduce the thermal loads affecting the truck cabin, to reduce the need for AC use. This would increase the fuel economy, reduce the associated fuel costs, and decrease the tailpipe emissions, thus contributing to health benefits and climate change mitigation.

Several studies have been conducted about the thermal loads affecting the cabin of vehicles and the strategies to reduce them. Han and Chen (2009) used a computational fluid dynamics approach to simulate the cooling performance of an AC system in a passenger car, for different properties of the vehicle materials. The authors report that a solar reflective glazing on the windows and windshield could reduce the temperature inside the cabin and improve the thermal comfort of the passenger. However, their analysis focused only on the optical properties of the windows of a south-oriented parked car, during solar peak hours with constant ambient temperature, thus limiting the relevance of their findings to a very specific setting. The influence of the optical properties of the external paint was analyzed by Lustbader and coworkers, who reported that switching from a black to a white paint could reduce the daily AC power consumption by up to 21% in parked heavy-duty trucks (Lustbader et al., 2014). Yet, the analysis focused on idling periods, which imply very different thermal loads on the cabin and, thus, do not reflect the AC use and associated fuel consumption of moving vehicles under normal operation. Rugh and coworkers tested both solar reflective glazing and paint on a passenger car parked during summer conditions, to determine their impact on the AC system and estimate the potential reduction in fuel consumption (J. P. Rugh et al., 2007). They reported a 30% reduction in the cooling load and estimated a 26% reduction in the AC-related fuel consumption. Levinson and coworkers used a similar approach to study the impact of solar reflective paints on the AC use, fuel consumption and emissions (Levinson et al., 2011). They reported that when the car shell reflectivity was increased by 0.5, soak temperatures decreased by 5–6 °C, and that opting for a white-colored shell (higher reflectivity) instead of a black-colored one (lower reflectivity) would lower fuel consumption by 0.21 L/100 km (1.9%) and CO_2 emissions by 4.9 g/km (1.9%). Although these works correlate changes in AC cooling load with fuel savings and reduction in emissions, they analyze soak temperatures during summer days, again limiting the scope of the analysis to a setting that is quite different from the scenario of a moving vehicle under normal operation. Rugh and coworkers analyzed the fuel consumed by the AC and its associated emissions for different regions of US and Europe (J Rugh et al., 2004), but they relied heavily on estimations of the AC usage percentage based on fixed input parameters, rather than on the actual thermal exchanges between the vehicle cabin and the environment throughout the day.

While the abovementioned works provide interesting data regarding the use of the AC system in vehicles and possible strategies to reduce it, most of them concern parked vehicles. This implies different load dynamics over time relative to those in a moving vehicle. In addition, they focus on summer conditions, which disregards the changes in AC use in the different seasons of the year. Furthermore, studies regarding heavy-duty trucks are scarce and the results of thermal loads affecting light passenger vehicles and the associated reduction in AC use should not be directly used to extrapolate for the case of heavy-duty trucks. This is because both vehicle types have very different cabin geometry and glazing-to-opaque surface area ratios, which change the thermal loads that have to be compensated for by the AC system.

The European Commission developed the Vehicle Energy Consumption calculation Tool (VECTO) to estimate the energy consumption, fuel consumption and CO_2 emissions of heavy-duty trucks in Europe in a standardized approach (Fontaras et al., 2013). It was developed to account for the different vehicle components/parameters that contribute to its overall energy consumption, based on data from manufacturers (i.e., braking, aerodynamic losses, gearbox or auxiliaries) and on different driving strategies (i.e., engine stop-start, eco-roll or predictive cruise control). Yet, the energy consumption due to the AC can only be included in the VECTO calculations via a constant value over time, implying a constant cooling load inside the cabin, thus not reflecting real-world conditions with variable thermal loads. Moreover, the majority of respondents to a 2016 questionnaire on VECTO capabilities considered that the auxiliary loads and energy management options were “insufficiently captured” (Zacharof & Fontaras, 2016). Furthermore, although the importance of the AC efficiency and the paint and glazing reflectivity in the overall energy consumption of AC systems was acknowledged in the 2016 questionnaire results, these effects were not incorporated in the recent updates to VECTO (Rexeis et al., 2019). Therefore, there was a need for a tool predicting the AC cooling loads of heavy-duty trucks under different and non-constant thermal environments, where the effect of the truck cabin materials over its fuel consumption and tailpipe emissions were duly considered.

In Vale and coworkers, we followed a heat balance approach to study the thermal loads affecting the cabins of moving heavy-duty trucks, considering exposure to representative environmental conditions for a typical summer period in the south of Europe (Vale et al., 2021). We investigated the thermal loads and the associated AC cooling needs throughout the day, and the potential reductions that could be achieved by changing the optical properties of the truck cabin paint and glazing elements. We now build on the developed model and expand the analysis to account for the environmental conditions of the entire Europe in the four seasons of the year, considering the main four cardinal directions of the truck, and the real size of the truck fleet in each country. We assess the potential for reduction in the yearly fuel costs and tailpipe emissions at the continent level, which can be achieved by decreasing the cabin required AC loads via modifications in the properties of the truck cabin materials. For greater representativeness of the findings, all parameters used in this work were derived from weather observation data (i.e., solar radiation, temperature and humidity), existing products/materials (i.e., paint and glazing elements) and the existing truck fleets in the different European countries (i.e., fleet size).

Material and methods

In this section, we detail the modeling approach used to investigate the thermal loads and associated AC cooling needs of a truck cabin. These results are then used to estimate the corresponding fuel consumption, and the associated fuel costs and tailpipe emissions. We start by considering a single truck stationed in different European regions (each representing a distinct climate) exposed to the different seasons of the year. Then, the year-averaged results for a single truck are extrapolated for the entire truck fleet existing in each region. Finally, this analysis is repeated for different scenarios considering cabin materials with improved optical properties.

European heavy-duty trucks

Freight transport activities are continuously expanding in Europe. Total freight transport was 7.3% higher in 2013 than in 2000 (European Environment Agency, 2016b) and is expected to grow faster than passenger transport, increasing by 57% in 2050 relative to 2010 (European Environment Agency, 2016c). Most of the trucks in operation are of cab-over-engine type (Sharpe & Rodríguez, 2018), in which the front of the vehicle is relatively flat and aligned with the front windshield (DAF, 2019; Scania, 2019; Volvo Corporation, 2019), conforming with existing European length legislation. Of these, those heavier than 3.5 tonnes (i.e., N2 and N3 categories of the EU classification (UNECE, 2014)), are referred to as heavy-duty trucks. Heavy-duty trucks represented over 90% of the 2017 heavy-duty vehicle market share (ICCT, 2018) and are closely related with multiple sectors of the economy, because of the multiple distribution chains they support. Thus, gains in efficiency or productivity in the heavy-duty truck sector end up pouring into other sectors of the economy. For these reasons, we focused our study on this type of trucks considering as example the Volvo FH cab-over-engine truck whose specifications are publicly available (Volvo Corporation, 2019) and do not significantly differ from those of other manufacturers present in the European market (DAF, 2019; Scania, 2019). Building on our previous work with this type of vehicle (Vale et al., 2021), each surface of the virtual truck cabin (i.e., glazing and opaque elements) was considered homogenous and composed of existing materials with relevant properties (see Table 1 and Vale et al. (2021) for more details).

The European heavy-duty truck fleet consists of nearly 7 million trucks in use, spread across different countries (Figure 1; ACEA, 2018). The fleet sizes in each European country were used in the Results and Discussion section to extrapolate from the results for one truck to those for the entire fleet operating in Europe.

Mathematical Model

The total thermal load $\dot{Q}_{Tot}$ [W] on a truck cabin was calculated using a heat balance approach as the sum of the different loads affecting it (Vale et al., 2021):

$$\dot{Q}_{Tot} = \dot{Q}_{Met} + \dot{Q}_{Rad} + \dot{Q}_{Amb} + \dot{Q}_{Vent} + \dot{Q}_{AC} \quad (1)$$

where $\dot{Q}_{Met}$ [W] is the metabolic load of the driver and second passenger, $\dot{Q}_{Rad}$ [W] corresponds to the solar radiation load reaching the truck surfaces, $\dot{Q}_{Amb}$ [W] corresponds to the ambient load related to heat transfer by convection between the ambient air, the truck surfaces and the cabin air, $\dot{Q}_{Vent}$ [W] is the ventilation load associated with the air exchange between the ambient and the cabin due to leakage, and $\dot{Q}_{AC}$ is the AC load required to maintain a constant cabin internal temperature. Other loads related to the heat produced by the combustion engine and the heat of the exhaust gases are not considered as they are often much smaller than the other loads (Fayazbakhsh & Bahrami, 2013; Khayyam et al., 2009). More details regarding each of the variables considered in Eq.(1) and the validity of this approach, which was checked against numerical and experimental data in the literature, can be found in Vale et al. (2021).

The environmental conditions change throughout the day, and thus, most of the above loads vary over time. For that reason, the AC system, which is tasked with compensating for the loads affecting the cabin, adapts its cooling power over time to ensure a null total thermal load on the cabin, and a constant internal temperature. All the above loads were calculated over time at every 1 minute, assuming thermal equilibrium in each step, based on the data and reasoning detailed in the subsections below.

Weather and solar conditions

The contributions of the $\dot{Q}_{Rad}$ [W], $\dot{Q}_{Amb}$ [W] and $\dot{Q}_{Vent}$ [W] loads in Eq. (1) depend on the weather and solar radiation conditions the truck is subjected to. The different European countries have different climates, which therefore imply different cooling demands from the AC system. This results in different ancillary loads on the engine, and thus different fuel consumption. As these effects correlate with the typical local weather and solar radiation in each geography, we started by grouping European countries with similar climates into four regions (Figure 2), in line with the grouping adopted by the European thesaurus EuroVoc (European Union, 2019):

- Southern Europe (1.8 million trucks, 26%): Greece, Italy, Portugal, Spain;
- Western Europe (2.5 million trucks, 38%): Austria, Belgium, France, Germany, Ireland, Luxembourg, Netherlands, Switzerland, United Kingdom;

Table 1. Optical properties considered for the different cabin scenarios (see Vale et al., 2021, for more details).

Scenarios	Windshield				Side Windows				Paint			
	transmissivity (τ)	absorptivity (α)	reflectivity (ρ)	emissivity (ε)	transmissivity (τ)	absorptivity (α)	reflectivity (ρ)	emissivity (ε)	transmissivity (τ)	absorptivity (α)	reflectivity (ρ)	emissivity (ε)
Standard	0.50	0.45	0.05	0.95	0.49	0.46	0.05	0.95	0	0.68	0.32	0.90
Low-transmissivity windshield	0.33	0.20	0.47	0.95	0.49	0.46	0.05	0.95	0	0.68	0.32	0.90
Low-transmissivity side windows	0.50	0.45	0.05	0.95	0.33	0.20	0.47	0.95	0	0.68	0.32	0.90
High-reflectivity paint	0.50	0.45	0.05	0.95	0.49	0.46	0.05	0.95	0	0.30	0.70	0.88
Low-trans. glazing and High-refl. paint	0.33	0.20	0.47	0.95	0.33	0.20	0.47	0.95	0	0.30	0.70	0.88

- Eastern Europe (2 million trucks, 30%): Croatia, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia;
- Northern Europe (0.4 million trucks, 6%): Denmark, Estonia, Finland, Latvia, Lithuania, Norway, Sweden

Hourly temperatures were collected for the capital of each country from the TimeAndDate (Time & Date, 2019) database, for each day of the 2nd or middle month of each season (i.e., January for winter, April for spring, July for summer and October for autumn), taken as a good representation of that season data. Then, a fourth order polynomial was fitted to the data of each representative month of each capital (Figure 3a). Each region weather data was then obtained by averaging the relevant capitals fitted data (Figure 3b). A monthly average of the relative humidity was also calculated from data from the same database (see Appendix A for details on the fitting data).

Solar angles throughout the day were computed for each capital following the equations provided by NOAA (US Department of Commerce (2012); Figure 4a), and then averaged to obtain each region solar path in each season (Figure 4b). The direct and diffuse solar radiation components were calculated according to NASA's Prediction Of Worldwide Energy Resources (POWER) methodology (Stackhouse et al., 2018, p. 37), based on the top-of-atmosphere solar radiation and the sky clearness index. The top-of-atmosphere solar radiation was calculated based on the extra-terrestrial radiation (Duffie et al., 1985, p. 9) for the representative day of each month (Duffie et al., 1985, p. 14), and the monthly average of the sky clearness index was computed based on data obtained from the POWER database (NASA, 2019).

The weather and solar radiation data were used to assess the loads on the truck cabins for the environmental conditions prevailing in each of these seasons in the different regions of Europe (more details in Appendix A).

Boundary conditions

Heavy-duty trucks are often required to travel long distances which implies long periods of driving. Multi-manning, i.e., having the vehicle manned by at least two drivers, is preferred in such cases, as it allows for one driver to rest while the other is driving (Meyer & Kopfer, 2008) and full compliance with the EU legislation of mandatory rest periods (e.g., 45 minutes break after 4.5 hours driving (European Commission, 2013)). Moreover, it enables additional on-road time and is considered more profitable and safe (J. C. Johnson et al., 1975, pp. 277–287; Klauer et al., 2005). For this reason, a driver and a passenger were assumed to be inside the truck cabins, with metabolic heat productions of 85 W/m^2 and 55 W/m^2, respectively, as prescribed by ISO 8996:2004, 8996:2004 (2004). These heat productions contribute to the total metabolic load on the cabin via the $\dot{Q}_{Met}$ variable in Eq. (1).

The comfort temperature and relative humidity inside the truck cabins were assumed to be 23 °C and 50%, respectively, in accordance with the ASHRAE comfort standards (ASHRAE Standard, 2001, p. 151). The comfort temperature and humidity influence the cooling demand from the AC

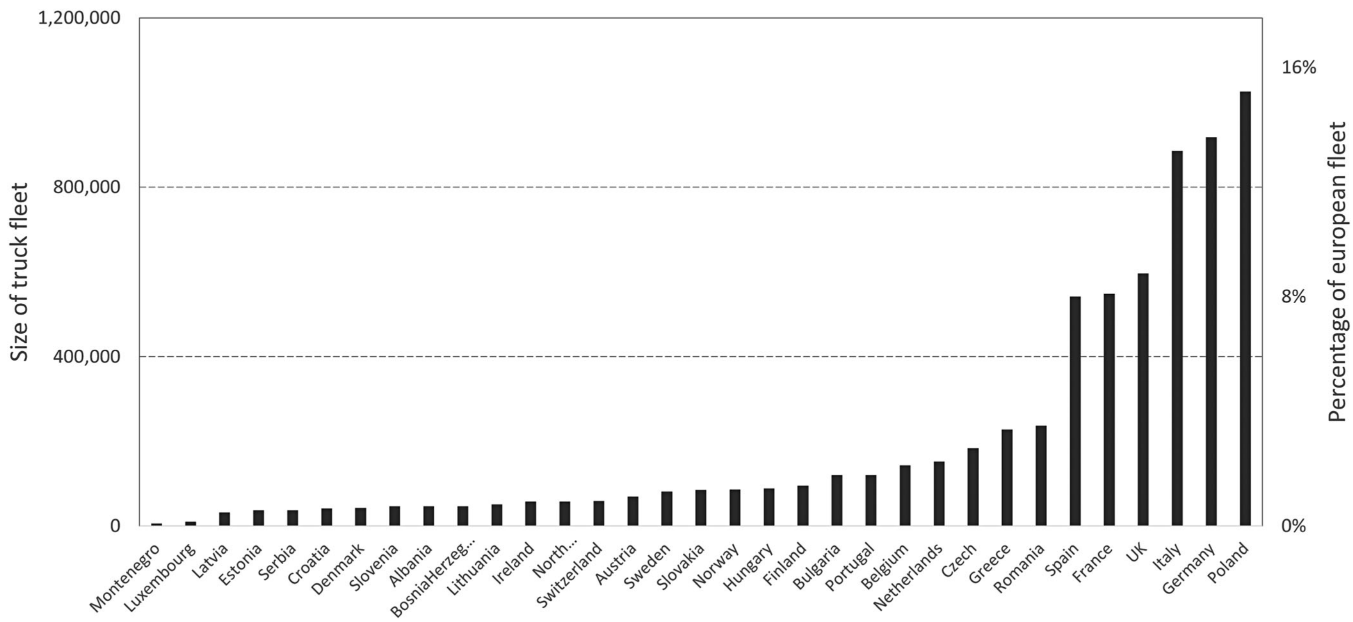

Figure 1. Number of trucks per country, as reported by ACEA (ACEA, 2018). Data for Albania, Bosnia and Herzegovina, Bulgaria, Montenegro, North Macedonia and Serbia was estimated from countries with similar annual road freight transport (OECD, 2018).

system ($\dot{Q}_{AC}$) via their effect over the ambient ($\dot{Q}_{Amb}$) and the ventilation ($\dot{Q}_{Vent}$) loads in Eq. (1) (see Vale et al., 2021 for details). The cabin air and truck surfaces were considered to be in thermal equilibrium with the surrounding environment at the beginning of the simulations. The fittings described in the Weather and Solar Conditions subsection were used to account for the variation in the hourly ambient temperature and solar radiation throughout the day, based on the season and region considered.

The virtual trucks were assumed to head north, east, south or west at 80 km/h, a typical speed in highway conditions. The thermal loads between 8:00 and 18:00 were calculated to capture the dynamics of the thermal exchanges of a typical workday schedule during sunshine hours.

Fuel consumption and tailpipe emissions

The AC main component is the compressor, which draws power from the vehicle engine to cool the cabin. Its cooling capacity is related to the compressor power by the coefficient of performance (COP), given by the ratio between the former two. We consider a COP value of 2 based on the range of values found in the literature (Andrew Pon Abraham & Mohanraj, 2019; Qi et al., 2010; Samuel et al., 2002). The vehicle AC maximum cooling load for the standard vapor-compression cycle system varies between 3 and 6 kW in different studies (Akyol & Kilic, 2010; Alkan & Hosoz, 2010; Hoke & Greiner, 2005; Levinson et al., 2011). For this reason, we assumed that our trucks' AC system had a peak cooling load in the middle of this range, i.e., 4.5 kW, and a maximum compressor power of 2.25 kW (i.e., 4.5 kW/2).

Tansini and coworkers analyzed VECTO simulation data from manufacturers and concluded that the fleet-averaged energy consumption due to the auxiliaries amounted to 5.6 kW, or about 5% of the truck fuel consumption (Tansini et al., 2019). This proportion indicates that an AC with a maximum compressor load of 2.25 kW increases the fuel consumption by up to 2%. Furthermore, in line with literature (Lee et al., 2013; J. P. Rugh et al., 2001), we assumed that the fuel consumption linearly increases with the cooling load provided by the AC system, up to the mentioned 2%.

The average baseline fuel consumption for a fully loaded truck considering different driving conditions is reported to be 35 L/100 km (Mårtensson, 2018), which means that the use of AC at maximum cooling load (i.e., 4.5 kW) increases the fuel consumption by 0.71 L/100 km (i.e., 2%). Therefore, we can estimate the AC fuel consumption (AC_{FC} [L/100 km]) using a linear interpolation considering the mentioned limits:

$$AC_{FC} = \frac{0.71}{4500} \cdot AC_{CL} = 1.59 \times 10^{-4} \cdot AC_{CL} \tag{2}$$

where AC_{CL} [W] corresponds to the load imposed by the AC system to maintain a comfort temperature inside the truck cabin.

Using the AC cooling loads required during typical days in each of the different seasons, and the associated fuel consumptions calculated via Eq. (2), we estimated the consumption for an entire year as the sum of the consumptions in each season:

$$AC_{FC}^{year} = AC_{FC}^{spring} + AC_{FC}^{summer} + AC_{FC}^{autumn} + AC_{FC}^{winter} \tag{3}$$

The average annual mileage of a heavy-duty truck in Europe (reported as 65,000 km, ICCT, 2016) was then used to obtain the total fuel consumed in a year due to AC usage, $fuel_{AC}^{year}$, calculated via Eq.(3):

$$fuel_{AC}^{year}[\mathrm{L}] = AC_{FC}^{year}\left[\frac{\mathrm{L}}{100\ \mathrm{km}}\right] \times 65,000\ \mathrm{km}/100 \tag{4}$$

The cost of AC use was assessed based on the average price per liter of fuel in Europe (1.346 €/L, European Commission Energy Policy, 2019) using the total fuel

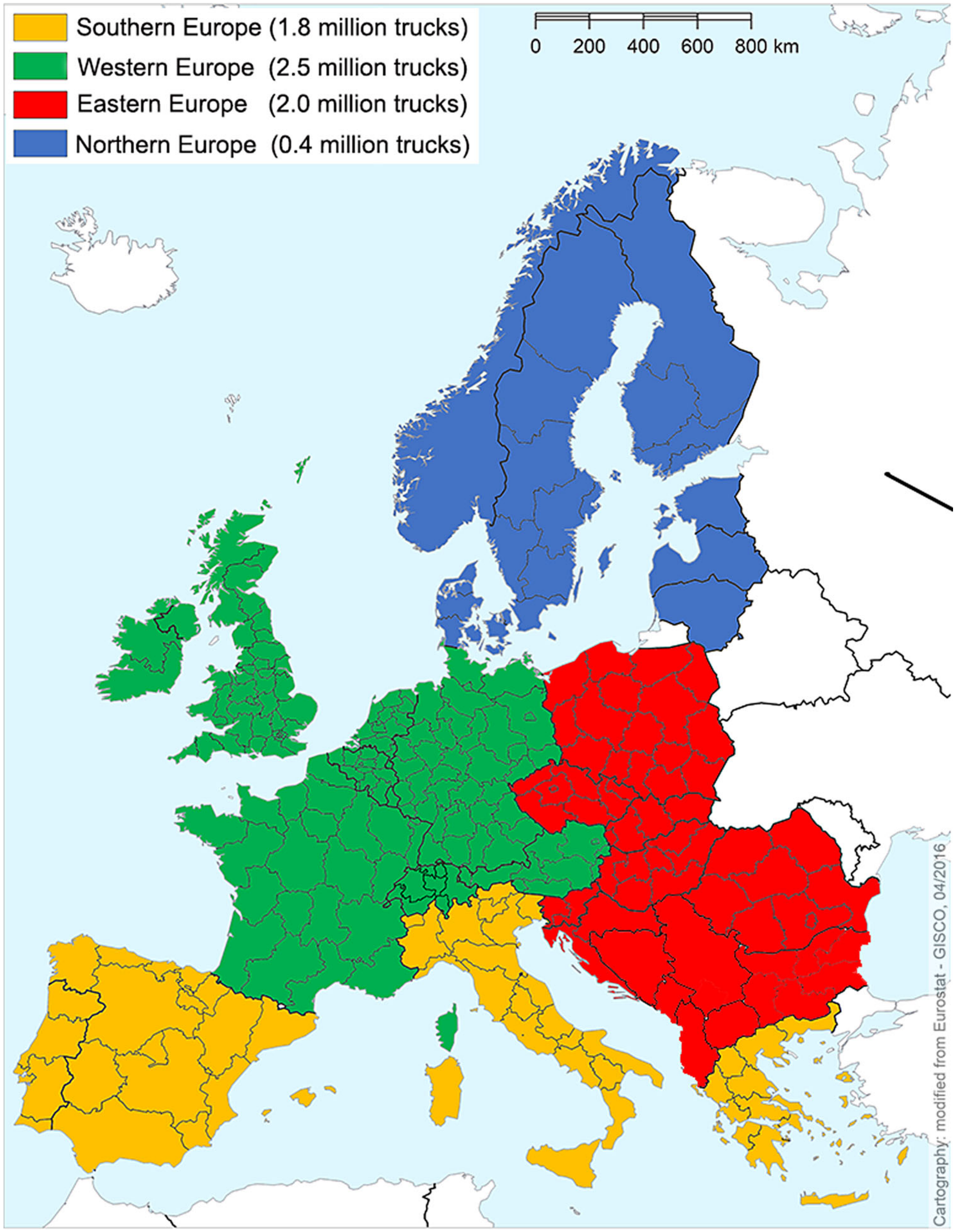

Figure 2. Grouping of the European countries into four regions, depending on the typical climatic patterns.

consumed in a year due to AC usage, calculated in Eq.(4). Furthermore, we considered that a typical Euro V type engine, produces 2.6 kg of CO_2, 7 g of NO_x and 0.1 g of PM, per liter of fuel consumed, as reported in the literature (Mårtensson, 2018). These relations together with the size of the truck fleets in the each of the European regions considered (Figures 1 and 2), allowed us to estimate the amount of pollutants associated to the AC-related fuel consumption, for all the heavy-duty trucks in Europe.

Scenarios considered

The thermal exchanges between a truck cabin and the surrounding environment are mostly influenced by the characteristics of the transparent surfaces, i.e., the windshield and the side windows, as well as the outer shell, i.e., the opaque surfaces protected by the paint. From these characteristics, it is the optical properties of these elements that have the biggest effect on the amount of heat entering the cabin (Levinson et al., 2011; J. P. Rugh et al., 2007; Vale et al., 2021), as they influence the solar radiation transmitted across the transparent surfaces or reflected by the opaque shell. For this reason, we investigated the effect of changing the optical properties of the windshield, side windows and external paint over the thermal loads affecting the cabin of heavy-duty trucks and the associated AC loads required to maintain a constant temperature.

We considered several scenarios for the heavy-duty trucks based on the properties of their cabin elements. A "standard" scenario (STANDARD, Table 1) regarded trucks with typical properties of the windshield, side windows and paint (Levinson et al., 2011; Mallick, 2012; Vale et al., 2021). We also considered a scenario with a low-transmissivity windshield, another with low-transmissivity side windows

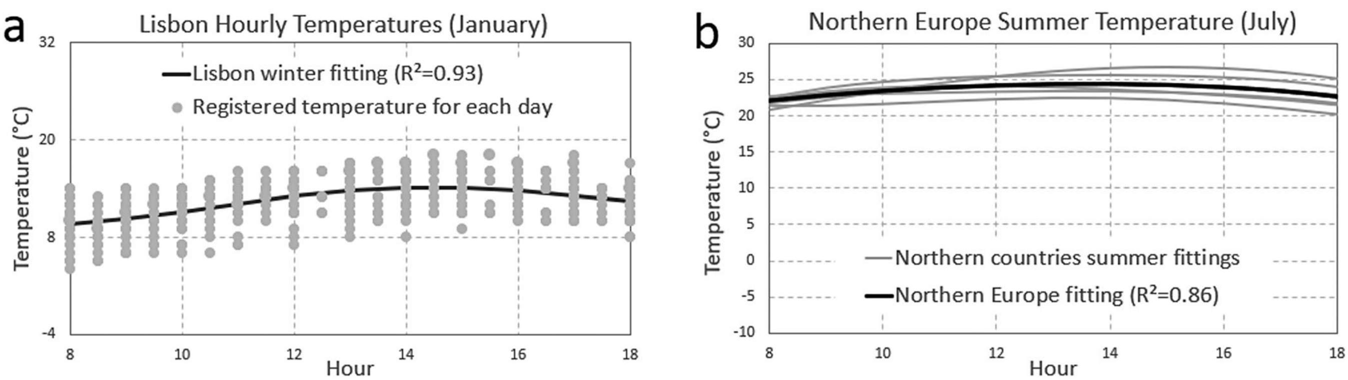

Figure 3. Hourly temperatures throughout the day and polynomial fittings; a) Daily data (grey dots) and fitting (black line) for Lisbon in winter (January 2018) and b) Data fittings for northern countries and average fitting for northern Europe in summer (July 2018).

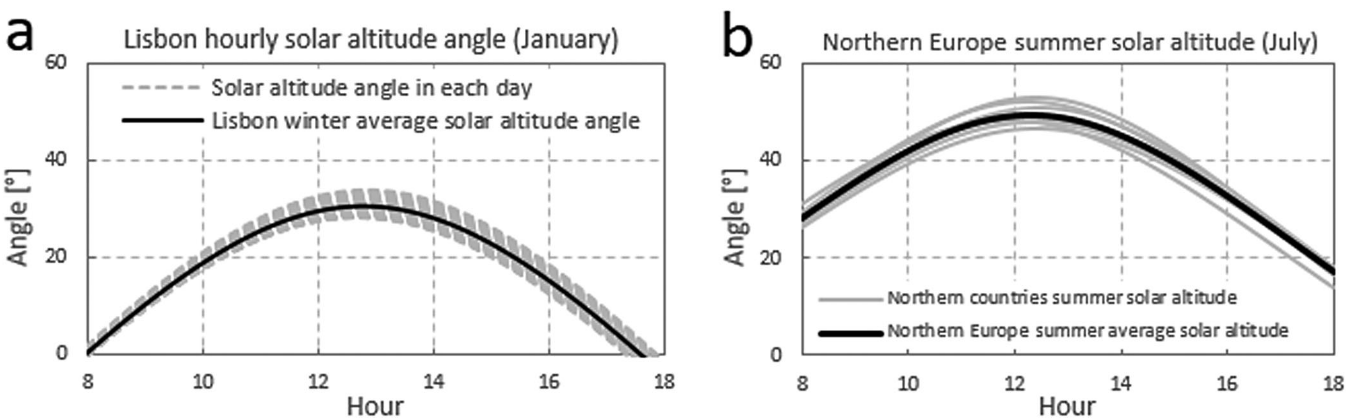

Figure 4. Hourly solar altitude angle and averaged values: a) January daily data and average values for Lisbon in winter (January 2018) and b) Averaged data for northern countries and average data for northern Europe in summer (July 2018).

and another with a high-reflectivity paint (Table 1). In the latter scenarios, only one cabin element was changed, with all the remaining elements being as in the standard truck scenario (Table 1). A final scenario (LOW-TRANS. GLAZING & HIGH-REFL. PAINT, Table 1) combining the modifications in the windshield, the side windows and the external paint was also considered. For greater representativeness of the results, the properties of the low-transmissivity glass and the high reflectivity paint considered in each scenario were based on commercially available products (e.g., Sungate® for the glass [19,58], known for having very low transmissivity, and the paints with the highest reflectivity value in the CoolCars database (Levinson et al., 2011)).

Simulated cases

The thermal loads affecting the cabin in each simulation case were assessed considering the specific properties of the cabin (i.e., cabin scenario), the direction of the truck (i.e., north, east, south and west) and the environmental conditions of each specific European region (i.e., southern, western, eastern and northern Europe) in each season (i.e., spring, summer, autumn, winter). The combination of all these cases resulted in a total of 320 different simulation cases, i.e., 5 truck cabin scenarios × 4 directions × 4 regions × 4 seasons.

Results and discussion

Thermal loads, AC costs and tailpipe emissions for a standard truck

We first calculated the cooling needs of a standard truck exposed to the typical thermal environments of each season, to assess the AC-related fuel costs in the different European regions. Figure 5a shows the average AC cooling load required to maintain comfort conditions inside the cabin of a single truck between 8:00 and 18:00, for each European region and season of the year. The estimated AC-related fuel costs are presented in Figure 5b, based on an average annual mileage of 65,000 km assumed evenly distributed along the year, i.e., 16,250 km per season.

As expected, a standard truck operating in southern Europe has the highest cooling needs (up to ≈1.2 kW/day; Figure 5a) and associated fuel costs (≈75 €/year, Figure 5b), because it relies more on the AC throughout the year to maintain a comfort temperature inside the cabin. On the other hand, northern European trucks depend the least on the AC to maintain a comfort temperature, with cooling being needed only in summer (≈0.8 kW/day; Figure 5a). This is the direct result of the very different temperatures and solar loads on both regions. Thus, cabin modifications that can reduce the cooling loads have a stronger impact in southern Europe, because they are felt for longer periods and the required cooling loads are higher (Figure 5a).

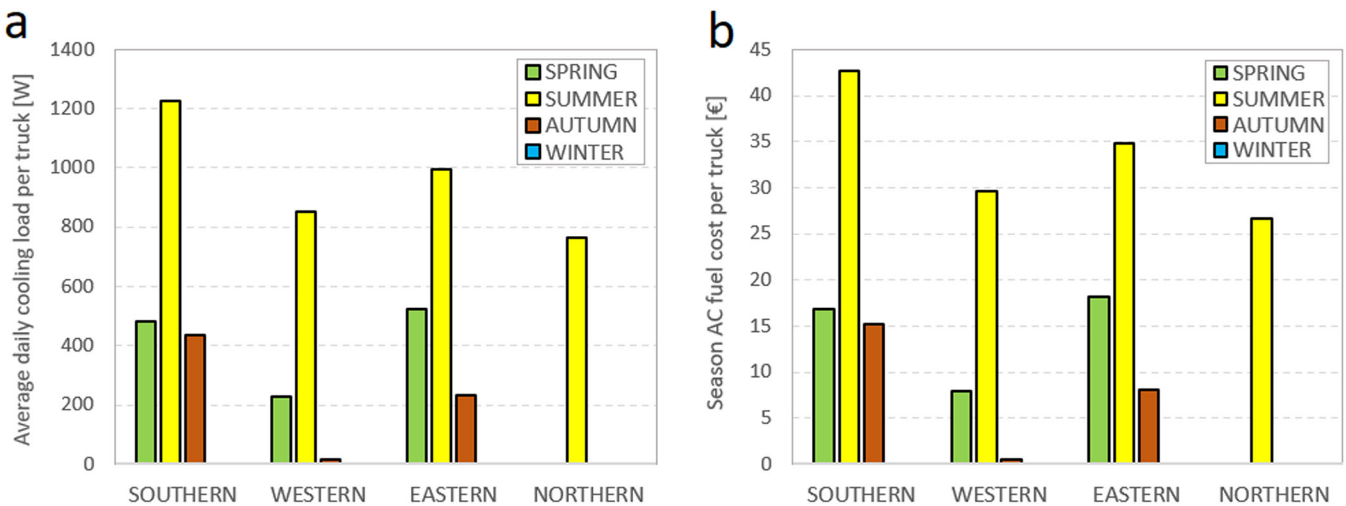

Figure 5. Cooling loads and associated costs per truck in each season and European region; (a) average daily cooling loads and (b) associated season AC-related fuel costs.

Nevertheless, all regions can benefit from such modifications since they all require cooling during summer, which is the season accounting for the largest portion of the yearly AC-related fuel costs, from 57% in the southern Europe to 100% in the northern Europe (Figure 5b).

To assess the global fuel costs of AC use in Europe, we considered the implications of the above figures for the entire truck fleet in each European region. Taking into account the AC fuel costs per truck in each season (Figure 5b) and the size of the truck fleet in each region (Figure 2), we obtained yearly AC fuel costs ranging from ≈€11 million in northern Europe to ≈€133 million in southern Europe (Figure 6), in a total of ≈€364 million for the entire Europe.

Southern Europe, being the most affected region, represents 36% of the European fuel costs due to AC use (Figure 6), despite having only 26% of the European truck fleet (Figure 2). This share of the costs is 12 times higher than that of northern Europe, which represents only 3% of the yearly European AC fuel costs, and 8–37% higher than that of the eastern/western regions (Figure 6). The elevated fuel costs observed in eastern Europe are due to the high cooling needs throughout the year (Figure 5a) and the size of the truck fleet, which is the second largest in Europe (30%, Figure 2 and Weather and Solar Conditions subsection).

If the baseline consumption of the trucks (i.e., 35 L/100 km) is also considered, the AC-related fuel costs represent between 0.1% (northern region) to 0.25% (southern region) of the yearly total fuel costs of each region. Overall, the European heavy-duty truck fleet has a total yearly fuel cost of ≈€208,000 million, from which the AC-related fuel costs represent ≈€364 million (≈0.18%).

The estimated yearly AC-related combined emissions of CO_2, NO_x and PM in each European region are shown in Figure 6, where we see that the two regions with the highest cooling needs (southern and eastern European regions, Figure 5a) account for more than two-thirds of the heavy-duty trucks total AC-related emissions (Figure 6). Given the relations between fuel consumption and emitted pollutants mentioned in the Fuel Consumption and Tailpipe Emissions subsection, the results of Figure 6 translate to emissions of ≈705 kilotonnes of CO_2, ≈2 kilotonnes of NO_x and ≈30 tonnes of PM for the entire Europe due to use of AC in heavy-duty trucks. According to the European Environmental Agency (EEA), heavy-duty trucks were responsible for the emission of ≈230 megatonnes of CO_2, ≈1 megatonne of NO_x and ≈40 kilotonnes of PM in Europe in 2017 (European Environment Agency, 2015, 2021). This means that the use of AC accounts for ≈0.3%, ≈0.2% and ≈0.1% of the CO_2, NO_x and PM emissions of heavy-duty trucks, respectively.

The estimated footprint of the AC system in the truck fuel costs and associated emissions highlights the importance of efforts to reduce the loads affecting the truck cabins and the related AC needs, in particular in the southern and central regions of Europe.

Thermal loads, AC costs and tailpipe emissions for optimized cabins

Given the relevant footprint of the AC in the overall fuel consumption and associated tailpipe emissions of heavy-duty trucks, we investigated the effect of modifying the properties of the cabin materials on the obtained AC cooling needs, associated fuel costs and emissions. Four sustainable solutions (i.e., independent modifications of the cabin properties, cabin scenarios in Table 1) that could lower the AC cooling loads were investigated, namely (i) using a low-transmissivity windshield, (ii) using low-transmissivity side windows, (iii) using a high-reflectivity external paint and (iv) combining the three previous solutions/modifications. The analyses described in the first Results and Discussion subsection were repeated but now considering five cabin scenarios, i.e., the standard truck plus the four optimized cabins [i.e., (i)–(iv) above]. Figure 7a shows the average daily cooling loads per truck for each scenario and European region, after averaging the results of the different seasons and truck directions. Figure 7b shows the associated fuel costs.

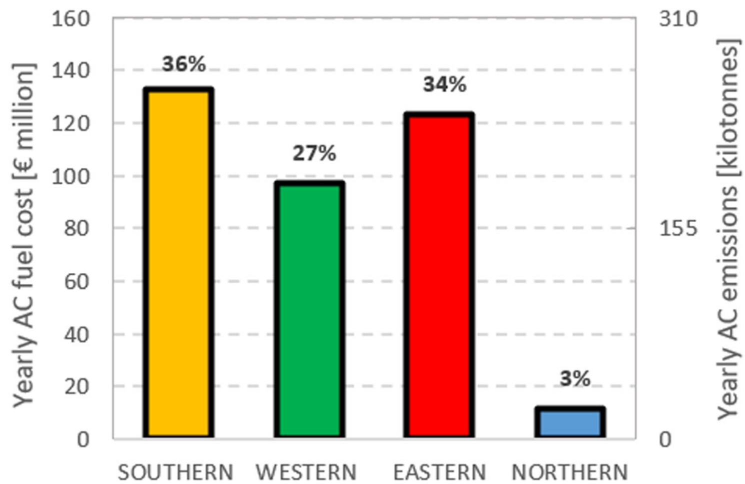

Figure 6. Estimated yearly AC-related fuel costs and emissions (PM, NO_x and CO_2 combined), for each European region.

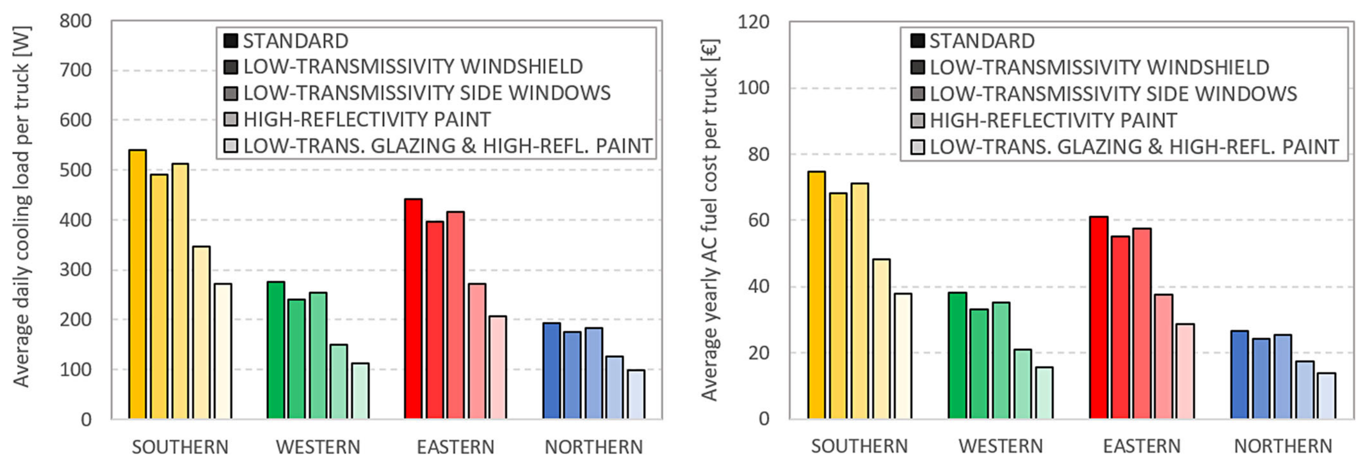

Figure 7. Cooling loads and associated costs per truck for each cabin scenario and European region; (a) average daily cooling loads and (b) associated yearly AC-related fuel costs; results obtained by averaging the data for different seasons and truck directions.

The windshield and side windows account for only 6% and 5% of the total surface area of the cabin (Vale et al., 2021), respectively, and for that reason, truck cabins featuring low-transmissivity glass ($\tau = 0.33$, Table 1) do not have vastly lower cooling needs than those with standard glass ($\tau = 0.50$). Changing to low-transmissivity side windows (Table 1) reduces the AC cooling load and associated yearly costs by 5–7%, while changing to a low-transmissivity windshield (Table 1) reduces the AC load and costs by 9–13% (Figure 7). On the other hand, the truck external painted surfaces account for 89% of the total surface area of the cabin, meaning that changing from a standard ($\rho = 0.32$) to a high-reflectivity paint ($\rho = 0.70$, Table 1) strongly reduces the average AC cooling needs and associated costs of a truck, i.e., by 35–45% (Figure 7a).

Combining the mentioned modifications to the windshield, the side windows, and external paint (i.e., LOW-TRANS. GLAZING & HIGH-REFL. PAINT in Table 1 and Figure 7) implies even bigger reductions in the daily AC cooling needs and associated costs—around 50% in all regions (Figure 7), which is 1.4–3 times higher than when modifying just the side windows, the windshield or the paint of the external surface alone.

The fuel costs and environmental impact of the mentioned modifications becomes evident when considering the entire truck fleet in each region over an entire year. We show those results in Figure 8 for the standard truck and the two most relevant modifications discussed above: the truck with high-reflectivity paint and the one with the combined modifications in the glazing and paint.

The southern and eastern regions are those that can benefit the most from the mentioned modifications, given their high cooling needs throughout the year (Figure 5a). The use of a high-reflectivity paint can reduce costs by ≈€47 million per year in both regions, and the reduction reaches ≈€66 million when combining the glazing and paint modifications. On the other hand, northern Europe, with its low cooling needs and small truck fleet can reduce AC fuel cost by only ≈€4–6 million, i.e., 12 times less than their southern and eastern counterparts.

Overall, if all European heavy-duty trucks were to use high-reflectivity paints in the external cabin surfaces, their AC-related fuel costs would decrease by ≈€142 million (39%, Figure 8a) per year. With the combined modifications in the glazing and paint, this reduction could reach ≈€195 million (53%, Figure 8a). This represents a reduction of ≈0.1% of the total yearly fuel costs, and thus of the truck emissions, of the entire European heavy-duty truck fleet. Interestingly, the results in Figure 8b show a reduction of 375 kilotonnes in CO_2

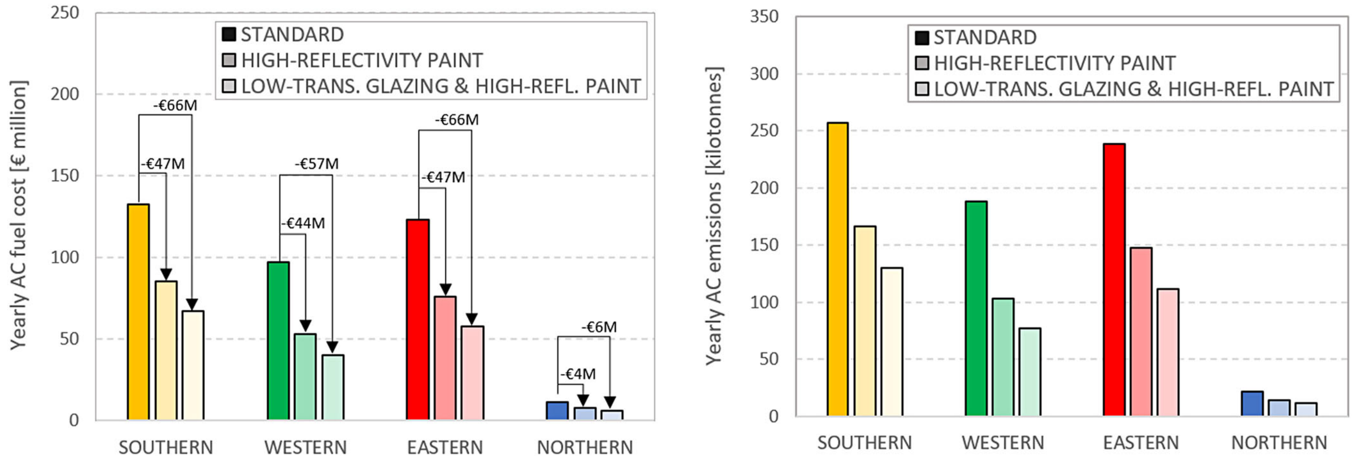

Figure 8. Estimated AC fuel costs and emissions for the standard, high-reflectivity paint, and low-transmissivity glazing and high-reflectivity paint scenarios in each European region, for the entire truck fleet; (a) yearly AC fuel costs and (b) yearly AC emissions.

emissions, which represent ≈0.2 percentage points of the 2025 goal of 15% reduction in emissions of heavy-duty trucks (relative to ≈230 megatonnes in 2017, (ICCT, 2019).

Our results highlight the importance of the optical properties of the cabin materials on the loads to be imposed by the AC systems and inform on the magnitude of the potential savings that can be achieved, for the entire European heavy-duty fleet. Furthermore, they offer an idea of the reduction in fuel costs and emissions that may be obtained at the continental level, particularly if considering also the European light-duty truck fleet, which is (i) also involved in multiple trips throughout the day due to the distribution chains they serve (e.g., national level of distribution, that comprises two-thirds of the total road distribution of Europe (Eurostat, 2019)); (ii) is ≈5 times larger than the heavy-duty fleet (ACEA, 2018), and (iii) have AC systems with ≈8 times larger footprint in terms of the trucks fuel consumption (the AC use in light-duty trucks is reported to increase fuel consumption up to 16% (V. H. Johnson, 2002)). Although more research will be needed to quantify the exact potential reduction in fuel consumption and emissions for different types of vehicles, overall, these results emphasize the relevance of privileging sustainable solutions for reducing AC fuel costs and tailpipe emissions associated to the road transportation in Europe. Finally, although the recurrent nature of the mentioned potential reductions in the fuel consumption and associated emissions, and the increasingly tighter regulations of combustion-based vehicle emissions, should serve as strong incentives for the transportation operators to accommodate the one-off costs of adapting the trucks glazing and paints, it would be important for the transportation policymakers and regulating bodies to consider the use of temporary measures and/or incentives to promote the faster adaptation of the European truck fleets.

Limitations of the study

Although the modeling approach used in this analysis (Vale et al., 2021) had been validated against numerical and experimental works in the literature, it still incorporates a series of assumptions and simplifications that should be acknowledged. We based the analysis on a cab-over-engine truck since it is a good representation of the typical European heavy-duty truck. However, the cabin geometry and the glazing to surface area ratios may vary between different brand/models, which may affect the AC loads and the associated fuel consumption. Additionally, using data from the literature, we assumed that the use of AC could increase the fuel consumption by up to 2%. Yet, it is possible that the AC-related fuel consumption of the different truck brands and/or AC systems may be somewhat different from the assumed 2%, which would imply different footprints in terms of fuel consumption and associated emissions.

The AC loads and the associated fuel consumption obtained in this work may also somewhat underestimate the AC loads and related fuel consumptions, of truck fleets in real-life scenarios. This is because we considered that the trucks were used in highway conditions, i.e., at high engine torques, whereas trucks used at lower velocities and/or lower torques may imply larger footprints in terms of fuel consumption of the AC system (AC-related fuel consumption generally decreases with increasing engine torque; Lee et al. (2013)). It is also worth mentioning that we considered the weather and solar radiation at the capital of each country as a good representation of the weather and solar radiation in the entire country. This assumption will be more or less accurate depending on how heterogeneous the weather patterns will be across each country territory. It is also important to consider that the fuel prices may vary across the different European regions, as well as over time, two effects that we did not account for in our analyses, and that could imply somewhat different proportions between the total fuel costs of the different regions analyzed. Finally, we focused our analysis on the potential reductions in fuel costs and tailpipe emissions that could be obtained by optimizing the optical properties of the glazing and external paint of the truck cabins. However, despite the recurrent nature of these potential reductions, one should have in mind that the capture of these potential reductions will require initial one-off investments by the transportation operators, investments that were considered beyond the scope of the present work.

Conclusions

We assessed the economic and environmental impact of AC use on the European heavy-duty truck sector to investigate the potential of different sustainable solutions to reduce the associated fuel consumption, fuel costs and tailpipe emissions. We conducted a numerical analysis of the thermal loads on heavy-duty trucks, considering the ambient conditions prevailing throughout the different seasons of the year in the different European regions. We studied the impact of modifications to the cabin windshield, side windows and external paint optical properties, on the total AC cooling needs, fuel costs and emissions of the trucks. We concluded that relevant reductions in AC-related fuel costs and tailpipe emissions can be obtained by privileging cabin materials that minimize the heat gain by solar radiation. Specifically, the use of high-reflectivity paints reflecting 70% of the solar radiation on the external opaque surfaces of the trucks can reduce the AC-related fuel costs and emissions by ≈40% (i.e., ≈€142 million per year) across Europe. Furthermore, the reduction in AC-related fuel costs and emissions can reach > 50%, or ≈€195 million per year, if the trucks also use windshield/side windows transmitting only 33% of the solar radiation. These substantial potential reductions represent up to ≈0.1% of the total fuel costs of the European heavy-duty truck sector. Furthermore, the mentioned >50% reduction in the emission of CO_2, the main pollutant emitted by heavy-duty trucks, represents 1% of the reduction target set for 2025 (relative to 2017 values).

Our results show that the heavy-duty transportation sector can obtain interesting reductions in the fuel consumption and associated costs as well as a lower environmental footprint by optimizing the optical properties of the trucks materials, to minimize the needed AC loads. Furthermore, our results suggest that important reductions in fuel costs and emissions may be obtained in the European transportation sector, if the described sustainable solutions were to be adopted also in the light-duty fleet, which is ≈5 times larger than the heavy-duty fleet and has a ≈ 8 times larger footprint in terms of the trucks fuel consumption. This highlights the relevance of engaging with transportation stakeholders (workers unions, vehicle manufacturers, policy makers, regulating bodies), to raise awareness about the potential benefits for the European transportation sector and the environment.

Competing interests

The authors have no competing interests to declare.

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Appendix A. Weather and Solar data

Table A1. Fitting coefficients of the fourth-order polynomial $f(x) = Ax^4 + Bx^3 + Cx^2 + Dx + E$ for the various regions and seasons; monthly average of the relative humidity (*RH*) and of the clearness index (K_T) for each region, in each season.

Spring	Coefficient A	Coefficient B	Coefficient C	Coefficient D	Coefficient E	R^2	RH (%)	K_T
Southern Europe	1.18×10^{-3}	-6.45×10^{-2}	1.17	-7.75	31.2	0.91	58	0.54
Western Europe	9.05×10^{-4}	-5.42×10^{-2}	1.06	-7.55	29.3	0.89	61	0.47
Eastern Europe	1.85×10^{-3}	-1.01×10^{-1}	1.82	-12.31	42.5	0.94	52	0.53
Northern Europe	9.98×10^{-4}	-5.45×10^{-2}	9.76×10^{-1}	-6.39	20.2	0.89	62	0.48
Summer								
Southern Europe	4.42×10^{-4}	-2.74×10^{-2}	4.92×10^{-1}	-2.50	26.14	0.94	47	0.65
Western Europe	-5.36×10^{-4}	2.65×10^{-2}	-5.94×10^{-1}	7.06	-8.73	0.90	49	0.53
Eastern Europe	1.48×10^{-4}	-8.57×10^{-3}	5.14×10^{-2}	1.76	10.09	0.89	58	0.52
Northern Europe	-2.79×10^{-4}	1.25×10^{-2}	-2.80×10^{-1}	3.47	6.93	0.86	57	0.52
Autumn								
Southern Europe	1.22×10^{-3}	-5.99×10^{-2}	8.92×10^{-1}	-3.24	9.51	0.92	61	0.54
Western Europe	2.79×10^{-3}	-1.50×10^{-1}	2.80	-20.91	64.59	0.93	69	0.45
Eastern Europe	3.24×10^{-3}	-1.66×10^{-1}	2.89	-19.53	56.92	0.94	61	0.48
Northern Europe	1.18×10^{-3}	-5.44×10^{-2}	7.83×10^{-1}	-3.29	7.11	0.90	79	0.36
Winter								
Southern Europe	2.15×10^{-3}	-1.15×10^{-1}	2.11	-15.16	44.06	0.91	70	0.49
Western Europe	1.27×10^{-3}	-6.64×10^{-2}	1.20	-8.55	24.94	0.85	84	0.28
Eastern Europe	2.23×10^{-3}	-1.12×10^{-1}	1.90	-12.24	26.73	0.87	79	0.37
Northern Europe	2.52×10^{-4}	-1.01×10^{-2}	9.69×10^{-2}	3.79×10^{-1}	-7.07	0.81	88	0.20

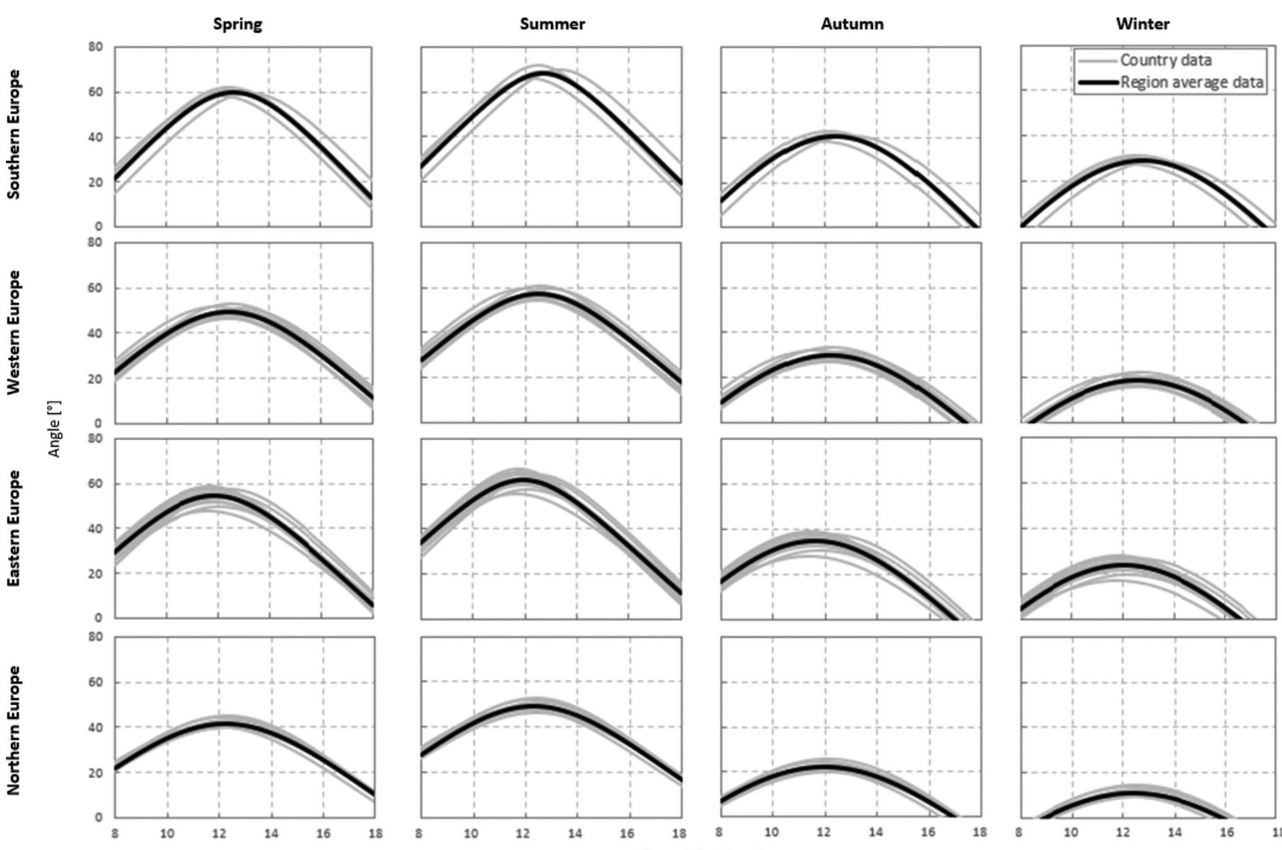

Figure A1. Solar altitude angle throughout the day, averaged for each region and season.

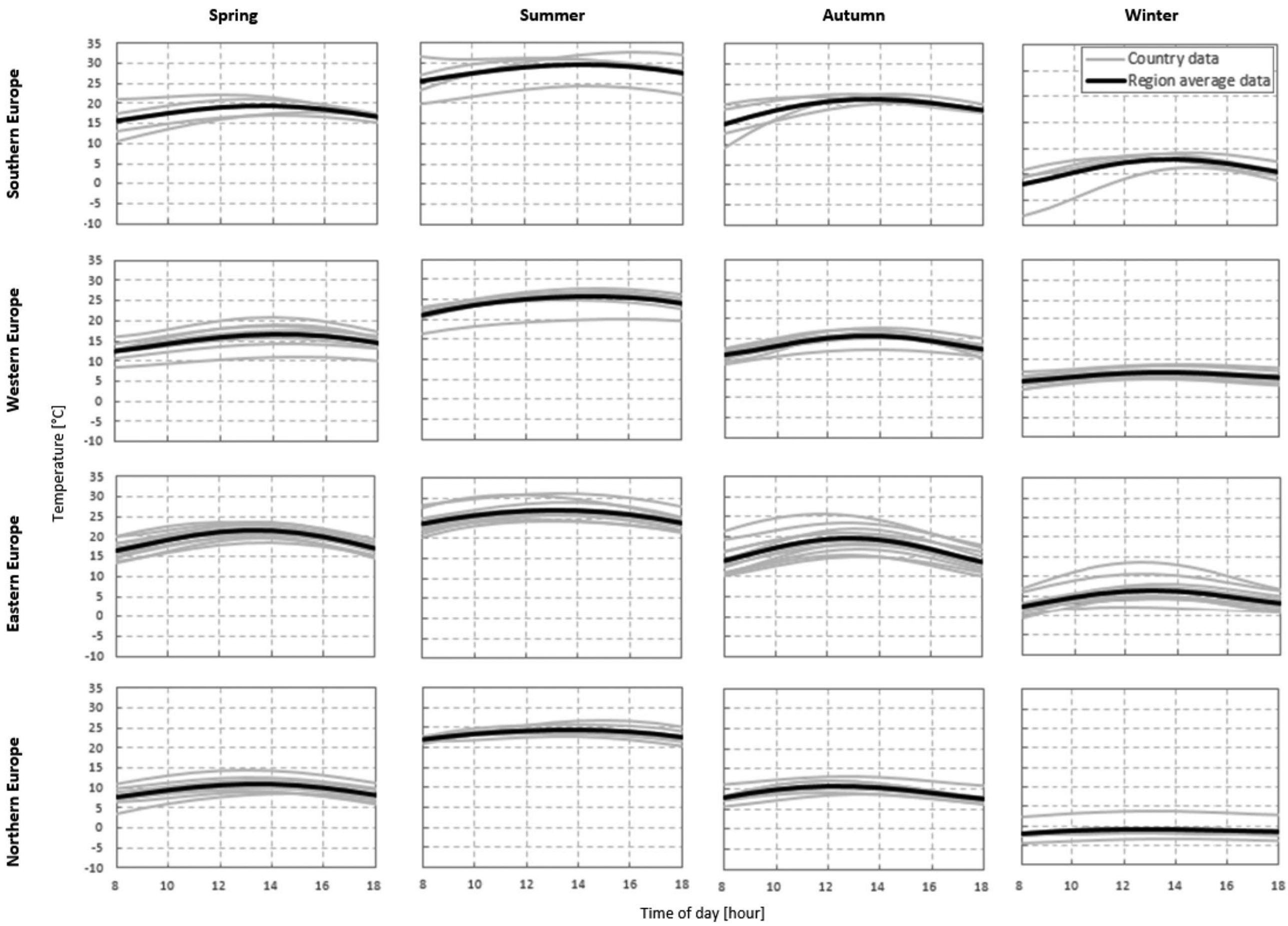

Figure A2. Ambient temperature throughout the day for the various regions and seasons, obtained by fitting a fourth-order polynomial to real world observations.

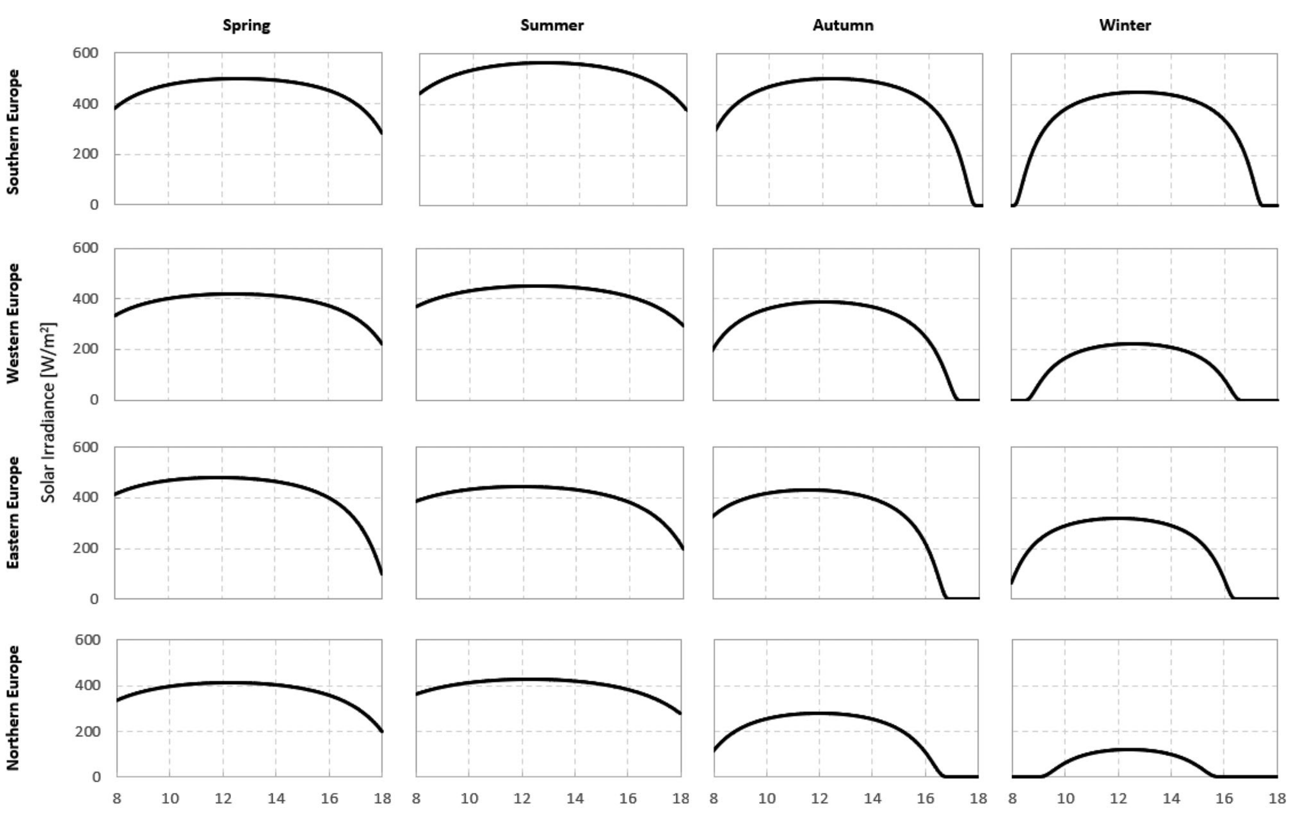

Figure A3. Solar irradiance [W/m2] throughout the day, for each region and season.