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Effectiveness of emissions standards on automotive evaporative emissions in Europe under normal and extreme temperature conditions

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E-mail: jsfu@utk.edu and michael.tschantz@ingevity.com**Keywords:** ORVR, NMVOC, heatwave, evaporative emission, driving cycleSupplementary material for this article is available [online](#)

Abstract

Non-methane volatile organic compounds (NMVOCs) are primary precursors for the formation of ozone and secondary organic aerosol which contribute to increased public health risks. Throughout Europe, passenger vehicles contribute significantly to NMVOC emissions due to automotive evaporative emissions controls that are less stringent than those in the United States, Canada, China, and Brazil. Evaporative NMVOC emissions increase significantly, and associated air quality impacts are exacerbated, during periods of high temperature such as heatwaves, which continue to increase in frequency, duration, and intensity. Adoption of strict evaporative emission standards and controls such as onboard refueling vapor recovery systems (ORVR) can significantly reduce evaporative emissions during such events; however, emissions inventories used to inform policy decisions are developed using average temperature profiles which fail to capture the impact of heatwave events on evaporative emissions. This study evaluates the effectiveness of the previous generation (Euro5), current (Euro6d), and proposed (Euro7) emission control standards on evaporative emissions at high temporal and spatial resolution in western and central Europe during July 2019, a month in which a significant heatwave swept through the region. Using temperatures obtained from the Weather Research and Forecasting (WRF) model with observation data and an improved method for estimating evaporative emissions, it is estimated that per-vehicle evaporative NMVOC emissions within the study domain and period are reduced by 25.0% under current Euro6d standards and controls relative to Euro5 standards, and that proposed Euro7 controls, including ORVR, would provide an additional 35.3% emissions reduction relative to Euro6d. During heatwave periods, Euro7 controls demonstrate improved attenuation of temperature-driven emissions increases relative to Euro6d controls, with associated emissions within the study period and domain increasing by 23.4% on average under Euro7 controls versus 29.4% under Euro6d controls. While this study does not quantify the effect of heatwaves and emissions controls on total annual emissions, the results for the study period of July 2019, combined with the low implementation cost of proposed Euro7 evaporative controls and projected continued dominance of petrol vehicles in the European fleet through the middle of this century, suggest that significant NMVOC emissions reductions and associated air quality and health impacts are achievable through the adoption of these more stringent standards and control systems.

1. Introduction/background

Passenger vehicles (classified under EU regulations as Category M vehicles) with petrol internal combustion engines (ICE) are significant contributors to anthropogenic non-methane volatile organic compound

(NMVOC) emissions throughout Europe. Along with nitrogen oxides (NO_x), NMVOCs are a primary precursor for the formation of ground-level ozone (O₃) [1] and secondary organic aerosols (SOAs) of fine particulate matter (PM_{2.5}) [2], which contribute to increased risk and incidence of acute and chronic cardiovascular and pulmonary diseases [3, 4]. NMVOC emissions from petrol ICE passenger vehicles result primarily from tailpipe exhaust emissions and evaporative emissions. Tailpipe emissions consist of unburned or partially burned fuel vapors, whereas evaporative emissions consist of volatilized fuel vapors that escape during refueling, as running losses during vehicle operation, by permeation of vapors through fuel tanks and supply lines, and as diurnal fuel tank breathing losses during parking events. While regulations have been implemented in many countries to reduce tailpipe exhaust NMVOC emissions, less effort has been made to regulate and reduce evaporative NMVOC emissions outside of the United States, Canada, China, and Brazil (USCCB), where O₃ and PM_{2.5} are subject to strict, enforceable air quality standards.

When stringent evaporative emissions regulations are implemented, evaporative NMVOC emissions from passenger petrol ICE vehicles can be equal to or less than exhaust NMVOC emissions; however, without adequate regulations and controls, evaporative NMVOC emissions have been repeatedly demonstrated to be significantly higher than exhaust NMVOC emissions [5, 6]. In Europe, passenger ICE vehicles are subject to less stringent evaporative emissions standards, resulting in significantly higher per-vehicle evaporative emissions in comparison to US vehicles regulated to Tier 3 emission standards.

ICE vehicles in most global markets incorporate an evaporative emission control system in the form of an activated carbon canister designed to adsorb petrol vapors from the fuel tank and utilize them in the engine for combustion, rather than being released to the atmosphere. In USCCB, stringent evaporative emission regulations have driven advancements in the design of these systems to better capture emissions from refueling, vehicle operation, and at least three days of diurnal vapor generation while parked. In other regions, including Europe and countries that follow European regulations such as through United Nations Economic Commission for Europe (UNECE) agreements, these canister systems remain undersized—being designed to control for only one or two days of diurnal vapor generation—and therefore lack the capacity to control emissions during refueling, parking events beyond two days, or during heatwaves.

In addition to in-vehicle activated carbon canisters, Europe also currently relies on Stage II vapor recovery systems installed in petrol stations to control the refueling portion of evaporative emissions. Stage II systems utilize passive or active vacuum-assisted fuel dispensers to capture and return vapors to underground bulk storage tanks during refueling. In Europe, the certification requirement for the efficiency of a Stage II system is 85%, as established in Directive 2009/126/EC [7]. However, the certification efficiency only applies to the capture of vapors by the nozzle at the nozzle/fill pipe interface at certification and does not address efficiency losses that can occur due to malfunctioning equipment, vapor leaks in the system, or the release of vapors from the underground storage tank vent stack that occur in operation. Early US Environmental Protection Agency (US EPA) studies estimated in-use efficiency of Stage II systems to be between 62%–92% [8] depending upon the frequency and rigor of maintenance and inspection; a more recent California Air Resources Board (CARB) study estimates Stage II efficiency to be around 71% [9]. To remain effective, Stage II systems require regular inspection and maintenance, the requirements for which are not as comprehensive in Europe [7] as those established in the US [10]. Furthermore, California systems include additional controls to prevent vapor venting from underground storage tanks by maintaining tank pressures within certain limits [11]. Considering estimated Stage II efficiencies in the US of 71% and the estimated Stage II implementation in Europe of 72% of all petrol stations [12], the actual efficiency of overall refueling emissions control in Europe is likely between 50%–60%.

To overcome the limitations of Stage II systems, regulations in USCCB require petrol ICE vehicles to be equipped with Onboard Refueling Vapor Recovery (ORVR) systems. In ORVR-equipped vehicles, a seal is formed inside the vehicle's filler neck during refueling to prevent the escape of fuel vapors, which are directed through a larger carbon canister system. In the US, over 20 years of data on ORVR implementation demonstrate that it can reliably capture at least 98% of evaporative NMVOC refueling emissions throughout the useful life of the vehicle [13]. While Stage II systems must be replaced periodically and incur annual operational costs, ORVR systems require no maintenance and can be installed on new vehicles at a cost of €10–€20 per vehicle [14]. During vehicle operation, fresh air is intermittently drawn through the ORVR canister to remove the adsorbed fuel vapor from the activated carbon. The stripped vapor is then fed to the engine for combustion, providing additional fuel savings that can offset a significant portion of the canister installation cost over the life of the vehicle [14].

Outside ORVR-equipped regions, many countries have been slow to adopt stricter evaporative emissions standards and tend to model air pollution and air quality regulations after those in Europe, where policymakers have chosen to adopt regulations requiring Stage II systems in lieu of ORVR. It should be noted that refueling emissions have traditionally not been considered within automotive evaporative emissions inventories and regulations in Europe; instead, refueling emissions are classified with the distribution of oil and gas products

[15]. This has historically led to the belief that evaporative emissions from vehicles are of the same magnitude as exhaust emissions; in reality, the evaporative component can be significantly larger when refueling emissions are included [5, 6]. In this study, refueling emissions are attributed to and considered part of the evaporative NMVOC emissions from passenger ICE vehicles, which also includes running losses such as leaks, permeation, and diurnal losses.

Regulatory decisions regarding evaporative emission control technologies and strategies are dependent upon accurately modeled estimates of evaporative NMVOC inventories. As a primary driver of evaporative processes, precise temperature input is vital to the accuracy of inventory estimates since evaporative emissions exhibit a non-linear dependence on temperature. However, evaporative emission inventories, including those used for European regulatory decisions, are often developed using average annual or seasonal temperature profiles that fail to capture extreme temperature events such as heatwaves—as seen in figure S5—which research suggests are increasing in frequency, duration, and intensity in response to climate changes [16].

This study aims to quantify the benefits of Euro7 emission control strategy options, which include stricter emissions limits and implementation of ORVR, by providing a high temporal and spatial resolution inventory of passenger ICE vehicle evaporative NMVOC emissions in Europe under past, current, and projected emissions controls and standards under normal and heatwave temperature conditions. The results indicate that significant emissions reductions are possible under proposed next-generation Euro7 standards with ORVR control systems and highlight the importance of considering extreme temperature events in the development of evaporative emissions standards and inventories in Europe to effectively evaluate proposed policy measures.

2. Methodology

A model for estimating diurnal, running loss, hot soak, permeation, and refueling evaporative emissions at high resolution was developed using the methodology described in our previous study [17], which expands upon Europe's COmputer Programme for calculating Emissions from Road Traffic (COPERT) and the US EPA's MOtor Vehicle Emission Simulator (MOVES) [18]—both of which are commonly used automotive emissions models—to better represent the evaporative components of automotive NMVOC emissions under real-world driving, parking, and refueling conditions. Whereas COPERT and MOVES utilize average temperature profiles to estimate annualized evaporative emissions at regional scales, the applied method better aligns with CARB and US EPA approaches in which regulatory decisions are made by analyzing the impact of proposed policies on reducing evaporative NMVOC emissions during summertime conditions in which air quality tends to be poorest. The method applied in this study evaluates the evaporative NMVOC emission inventory in Europe during a heatwave event by utilizing modeled temperatures obtained from the Weather Research and Forecasting model (WRF) [19] to provide a more accurate estimation of emissions at fine temporal and spatial resolution and scale. This method is applied to western and central Europe to determine hourly evaporative NMVOC emissions under Euro5 (past), Euro6d (current), and Euro 7 (proposed) emission control standards. The Euro 7 scenario includes recommendations by the Consortium for ultra-Low Vehicle Emissions (CLOVE) tasked by the European Commission with developing recommendations for Euro7 standards, which include more stringent emissions limits and implementation of ORVR [20]. Automotive fleet populations and compositions for each country within the domain were obtained from COPERT and Eurostat and were spatially distributed within a 0.1° (approximately 11-km) resolution grid according to the distribution of automotive sector NMVOC emissions within the EDGARv5.0 inventory [21]. To evaluate the impacts of typical temperatures and extreme temperature events, July 2019 was chosen as the modeling period due to a significant heatwave which impacted a large portion of central Europe from approximately July 21 to 27, during which record-high temperatures were recorded for many western and central European cities with ozone air quality exceedances also observed.

2.1. Meteorological modeling

To provide the locations without observational weather data, spatially and temporally continuous temperature inputs for the emissions model were obtained using WRFv4.2.1. The 11-km resolution modeling domain with a mesh size of 178×178 covers western and central Europe and is approximately bounded between 10°W to 15°E and 35°N to 55°N . Simulations were conducted for July 2019 and were initialized every 72 h at 1200 UTC from the European Centre for Medium-Range Weather Forecasts (ECMWF) 0.25°, 6-hour resolution ERA5 reanalysis data set [22]. Model parameterization was chosen based on published WRF studies of European domains [23] with Thompson microphysics scheme, Kain-Fritsch cumulus convection scheme, Dudhia shortwave radiation scheme, rapid radiative transfer method (RRTM) longwave radiation scheme, Yonsei University (YSU) planetary boundary layer scheme, MM5 surface layer scheme, and Noah land surface model parameterizations. Model performance for temperature is presented in figure S2 and includes observation data

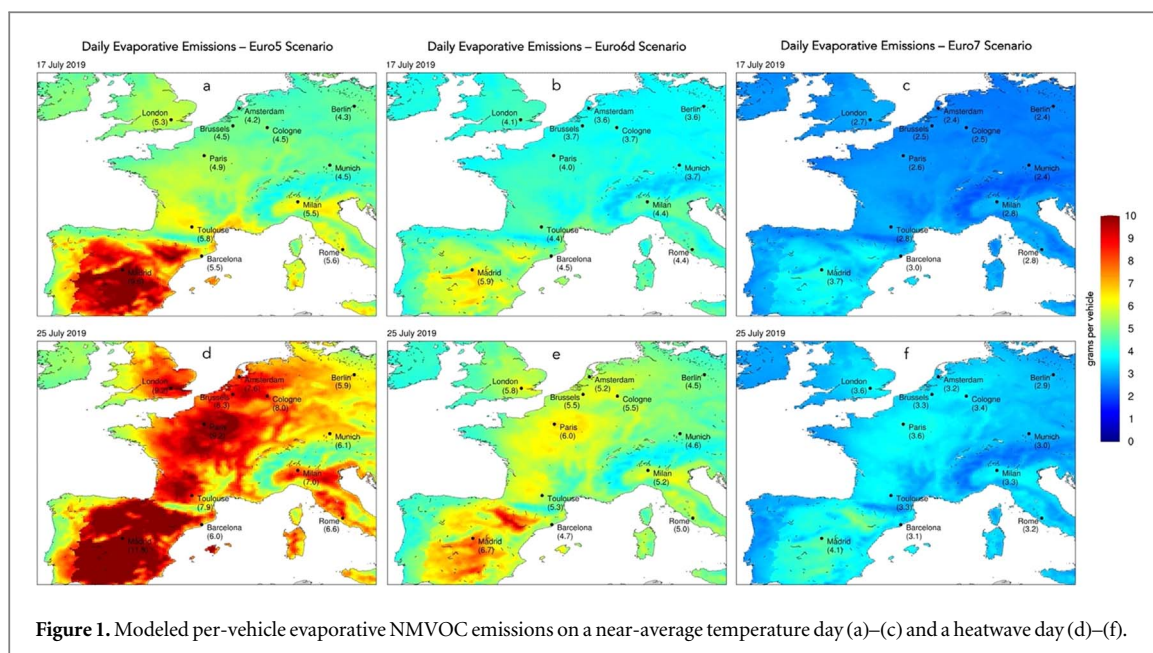
from 608 SYNOP weather stations; observations were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) global Integrated Surface Dataset (<https://www.ncei.noaa.gov/products/land-based-station/integrated-surface-database>). WRF-modeled temperature exhibited a bias and absolute error of -0.4°C and 2.0°C , respectively, which meet performance benchmarks for complex terrain [24] and indicate a slight underprediction of temperature on average. Figure S1 (available online at stacks.iop.org/ERC/4/081003/mmedia) highlights the difference in temperature at the same time of day between a near-average temperature day and the peak heatwave day throughout the domain, demonstrating the widespread impact of the late-July 2019 heatwave event.

2.2. Evaporative emissions modeling

The evaporative emissions model consists of MATLAB modules which calculate per-vehicle emission factors for diurnal, running loss, hot soak, permeation, and refueling sources. The frequencies and durations of driving and parking events, average trip numbers and distances, and average vehicle speeds were obtained from COPERT and were developed for use in Europe. For each scenario, inputs were adjusted to reflect European automotive evaporative emissions standards. Running loss, permeation, and hot soak rates were derived from methodologies applied in MOVES3 [18]; diurnal and refueling emissions were determined by methods described by Dong *et al* [17]. For all scenarios, in-use ethanol was set at 5%, which represents 84.3% of petrol sales in the EU [25]. Diurnal soak requirements used for canister sizing were one day for Euro5 and two days for Euro6d; canister sizing for Euro7 scenarios was based on ORVR. The full vehicle diurnal emissions limits were 2.0 grams for a 24-hour test, 2.0 grams for a 48-hr test, and 0.3 grams per day for a 48-hr test for Euro5, Euro6d, and Euro7, respectively. For Euro7, the stricter diurnal limit recommended by CLOVE (0.3 g/day) was chosen to align with the US Tier 3 standard; 0.5 g/day is an alternative suggested for EU standards [20] which aligns with current Brazilian PROCONVE L-7 standards. Canister purge volume was determined using the shortest drive cycle time from the New European Driving Cycle (NEDC) for Euro5 (60 min) and the World harmonized Light vehicle Test Procedures (WLTP) [26] for Euro6d and Euro7 scenarios (31.8 min) using methods described by Dong *et al* [17]. Evaporative emissions exhibit a linear relationship with fuel tank volume, so it was appropriate to use an average fuel tank capacity of 60 L which was determined based on fleet compositions within the domain. Carbon aging was accounted for by reducing the adsorption capacity of the carbon in the canister by 16% for the Euro5 scenario and 7% for the Euro6d and Euro7 scenarios, which represents the adoption of more durable carbon and the inclusion of aging procedures to ensure enhanced durability beginning with Euro6d standards. For each scenario, the model requires a base running loss and leak rate which reflect control measures, such as heat shielding designed to insulate fuel tanks and lines from radiative road surface heat during use, and on-board diagnostics designed to alert the driver of leaks in the fuel system. The base rate is then adjusted according to ambient temperature and Reid Vapor Pressure (RVP) to determine actual loss rates. Since Europe does not currently have a running loss standard or leak standard, emission factors for running loss and leaks were taken from conservatively low MOVES estimates for an enhanced or Tier 1 US vehicle for the Euro5 scenario (0.72 g hr^{-1}) and Tier 2 and 3 US vehicles for Euro6d and Euro7 scenarios (0.23 and 0.023 g hr^{-1} , respectively) [27]. Stage II efficiency was estimated as 60.35% based on the product of CARB's estimated in-use efficiency in the US of 71% and 85% implementation of Stage II in petrol stations throughout Europe, which was chosen to reflect the volume of fuel dispensed through petrol stations equipped with Stage II systems [7]. RVP values for each country within the modeling domain were aligned with COPERT inputs and gridded to match the WRF domain. All other modeling parameters are found in table S1 and were unchanged between scenarios.

3. Results

Grid-level emissions reductions achieved under Euro6d and projected Euro7 controls on a typical day with near-average temperatures and the peak heatwave day are shown in figure 1. On days with near-average temperatures, emissions remain relatively consistent throughout much of the domain except for the Iberian Peninsula due largely to Spain's exemption from European summer fuel standards intended to reduce petrol volatility by limiting fuel RVP to 60 kPa from April through September [28]. Spain's exemption, allowing the use of 68 kPa RVP petrol during extended summer months, was granted based on perceived increased costs to Spanish refineries to produce low volatility petrol during summer months [29] which, combined with its warm climate and high elevations, contributes to greater evaporative emissions in the peninsular region. It should also be noted that the intensity of the late-July heatwave was greatest in the region extending from France northeast through Germany, and the temperature anomaly in Spain was comparatively mild [30]. Within the study domain and period, exemptions allowing the use of 70 kPa petrol are also in place for the United Kingdom, Ireland, and Sweden, but cooler climates in these regions minimize the impact of higher fuel volatility on evaporative NMVOC emissions in comparison to Spain. Relative to previous generation Euro5 standards,



evaporative NMVOC emissions under current Euro6d standards are estimated to be 25.0 percent lower on average during the study period, with decreases of 24.4% on a near-average temperature day, represented by 17 July, and 27.5% on the peak heatwave day of 25 July. Under the presented Euro7 standards scenario, evaporative NMVOC emissions within the study domain and period are estimated to decrease by an additional 35.3 percent on average relative to current Euro6d standards as seen in figure S4, and with better attenuation of emissions spikes during heatwave days as seen in figure 2.

Table 1 highlights the differences in emissions under each scenario for several European cities and the percent reduction in NMVOC emissions over the previous generation of controls for a near-average temperate day and a heatwave day. Under current Euro6d controls, per-vehicle emissions are estimated to increase by as much as 50 percent on heatwave days, with an average increase of 29.4% amongst the twelve cities in figures 1 and 2. Under projected Euro7 controls, emissions are maintained 33%–40% lower than the Euro6d scenario, and emission increases during the heatwave period are limited to less than 40 percent, with an average increase of 23.4%, demonstrating that ORVR-equipped vehicles are more resilient to the breakthrough of emissions during periods of prolonged high temperatures due to the increased canister size.

Figure S3 highlights increased ambient O₃ concentrations observed during the hottest part of the study period, particularly in cities most affected by the late July heatwave (O₃ observations obtained from the European Environment Agency (EEA) at <https://discomap.eea.europa.eu/map/fme/AirQualityExport.htm>). Although this study does not elucidate the direct impacts of increased VOC emissions on air quality, recent chemical transport modeling efforts suggest air quality can be significantly improved following the implementation of ORVR and strict evaporative control standards in an automotive fleet [31]. It is reasonable to assume that the reduced emissions under the Euro7 scenario will provide quantifiable air quality improvements and associated health improvements—particularly in large metropolitan areas where photochemical ozone formation conditions are VOC limited. Applying EEA methodologies to estimate damage costs during the July 2019 study period results in an estimated damage cost reduction of approximately €5.1 million to €13.2 million under the Euro7 scenario relative to current standards; these damage cost estimates respectively represent the median value of a life year (VOLY) and the mean value of statistical life (VSL) approaches, which both include health impacts due to NMVOC as well as SOA and are assessed at €1,842/tonne and €4,800/tonne, inflation-adjusted to 2020 [32]. These estimates are based on annualized per-tonne damage costs assessed for NMVOC during the period of 2008–2012. It should be noted that per-tonne damage cost valuations can change over time as emission rates change; since 2010, transport-sector NMVOC emissions have been demonstrated to have continually and steadily increased globally and slightly decreased in Europe, while precursors to ozone and PM such as NO_x have decreased [33].

4. Summary, conclusions, and recommendations

Implementation of ORVR systems and stricter evaporative NMVOC emissions standards is a proven, cost-effective method to reduce automotive NMVOC emissions and associated health and economic impacts of

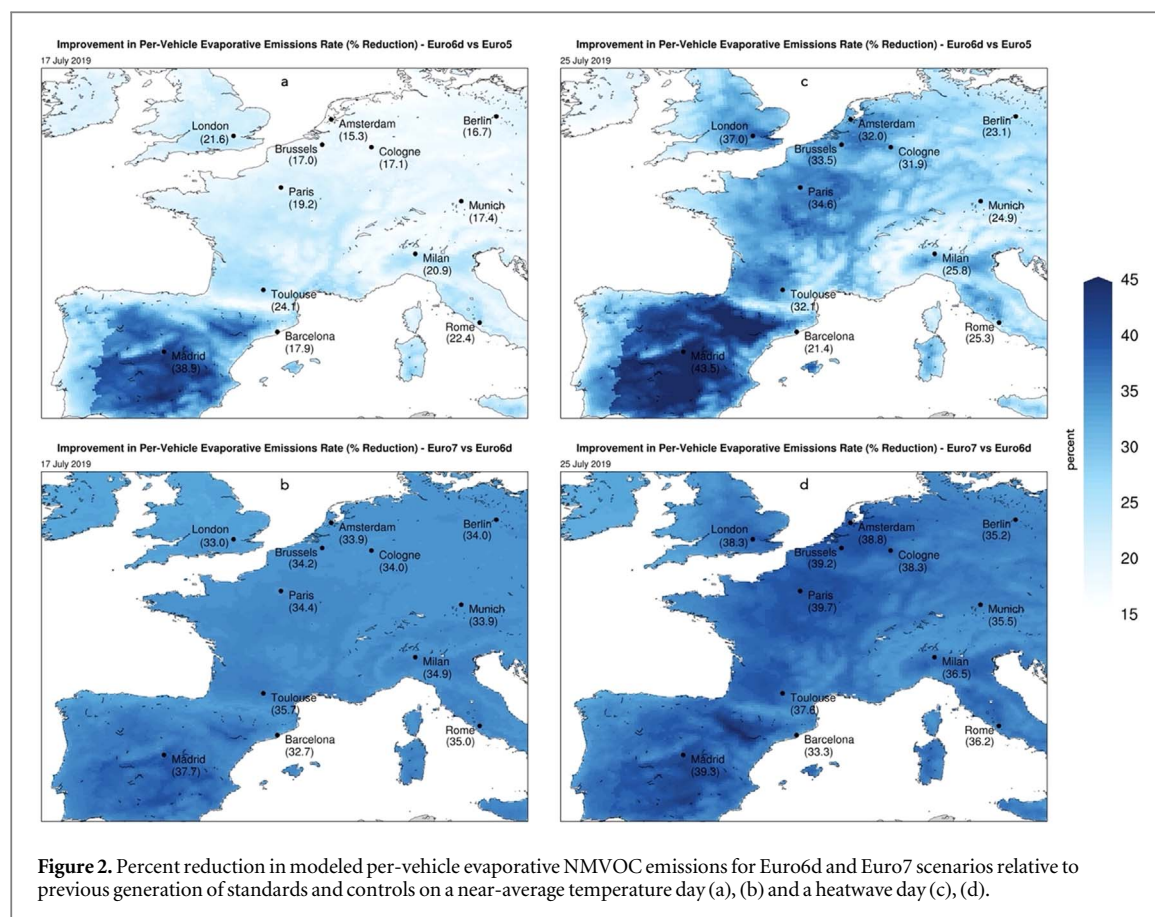


Table 1. Evaporative NMVOC emissions in grams per vehicle for select cities on a near-average temperature day and the peak heatwave day. Values in parenthesis indicate the percent change in per-vehicle emissions relative to the previous emission controls/standards scenario.

Location	Per-Vehicle Evaporative Emissions - g/vehicle									
	Euro5		Euro6d				Euro7			
	Near-avg temperature day	Heatwave day	Near-avg temperature day		Heatwave day		Near-avg temperature day		Heatwave day	
Amsterdam, ND	4.20	7.63	3.56	(−15.3)	5.19	(−32.0)	2.35	(−33.9)	3.17	(−38.8)
Barcelona, ES	5.48	5.95	4.50	(−17.9)	4.68	(−21.4)	3.02	(−32.7)	3.12	(−33.3)
Berlin, DE	4.32	5.86	3.60	(−16.7)	4.51	(−23.1)	2.37	(−34.0)	2.92	(−35.2)
Brussels, BE	4.50	8.26	3.73	(−17.0)	5.49	(−33.5)	2.46	(−34.2)	3.34	(−39.2)
Cologne, DE	4.52	8.04	3.74	(−17.1)	5.47	(−31.9)	2.47	(−34.0)	3.38	(−38.3)
London, UK	5.27	9.18	4.13	(−21.5)	5.79	(−37.0)	2.77	(−33.1)	3.57	(−38.3)
Madrid, ES	9.65	11.89	5.89	(−38.9)	6.71	(−43.5)	3.67	(−37.7)	4.07	(−39.3)
Milan, IT	5.53	7.04	4.37	(−20.8)	5.23	(−25.8)	2.85	(−34.9)	3.32	(−36.5)
Munich, DE	4.46	6.10	3.68	(−17.4)	4.59	(−24.9)	2.43	(−33.9)	2.96	(−35.5)
Paris, FR	4.92	9.22	3.97	(−19.2)	6.03	(−34.6)	2.60	(−34.4)	3.64	(−39.7)
Rome, IT	5.62	6.64	4.36	(−22.4)	4.96	(−25.3)	2.83	(−35.0)	3.17	(−36.2)
Toulouse, FR	5.82	7.85	4.42	(−24.1)	5.33	(−32.1)	2.84	(−35.7)	3.33	(−37.6)

increasingly more frequent extreme temperature events and a gradually warming climate. While increased electrification of the European passenger vehicle fleet is projected, petrol ICE vehicles—which include hybrid electric and plug-in hybrid electric vehicles—are also projected to continue to make up a significant portion of the fleet for the next few decades, and control of the associated evaporative emissions is critical to meeting short-term and future regional and global commitments to improving air quality. Many countries tend to model their regulations after those of the EU, and European implementation of stricter evaporative emission standards and ORVR control systems will likely spur the adoption of stricter policies in other regions. This influence is particularly important in developing countries—especially those in warmer climates such as India and Africa—where petrol ICE vehicles are likely to continue to dominate passenger vehicle fleets due to resource, funding,

and infrastructure limitations that may slow the adoption of electric vehicles, and where Stage II systems to control refueling emissions do not exist and ORVR systems can provide a much more significant reduction in evaporative emissions at a low cost.

This study also demonstrates the importance of using precise and accurate temperatures to estimate evaporative VOC inventories. Automotive evaporative emissions are highly sensitive to temperature, and emissions estimates made using average temperature profiles, such as those used by current COPERT methodologies for European inventories, fail to capture the impacts of extreme temperature events such as heatwaves and more commonly experienced extended periods of simply higher-than-average temperatures. It should also be noted that while US EPA's MOVES modeling system employs average temperature profiles for developing national emission inventories, regulatory decisions in the U.S. are based on worst-case, summertime scenarios in which the impact of policy on reducing emissions during extreme temperature events are considered. The methodology applied in this study can be utilized to develop more accurate evaporative emission inventories for use in regional air quality modeling efforts. The applied methodology is developed specifically for passenger cars, trucks, and SUVs, but it could be readily adapted for regions where motorcycles and other two- and three-wheeled vehicles make up a larger portion of the automotive fleet, such as parts of India and Southeast Asia.

Historically, diesel-powered vehicles have dominated the European passenger vehicle fleet. However, in recent years petrol has become the primary fuel type for European passenger vehicles, representing 51.7% of the EU fleet [34]. Despite increasing powertrain diversification and ambitious electrification goals, as of 2020 fully electric vehicles represented only 0.5 percent of EU passenger vehicles, and plug-in hybrid and hybrid electric vehicles combined accounted for only 1.8 percent [34]. It is important to note hybrid and hybrid electric vehicles still consume petrol and contribute to evaporative emissions and would benefit from improved evaporative emission controls. While IHS market projections suggest that electrified vehicles will continue to represent increasing proportions of new vehicle sales, petrol ICE vehicles are projected to represent the majority of EU passenger vehicle fleets through at least 2040 (ihsmarket.com).

While reductions in evaporative emissions have been realized under current Euro6d standards, the opportunity for significant improvement remains. Implementing ORVR and stricter emissions limitations in Europe will enable significant reductions in VOC emissions and aid European countries in meeting air quality standards and emission ceiling limits. Future efforts are recommended to focus on elucidating the direct air quality and health impacts of heatwaves and a gradually warming climate in areas that lack strict evaporative emissions controls through regional chemical transport modeling.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Declaration of competing financial interests

The authors declare they have no actual or potential competing financial interests.

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