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European type-approval test procedure for evaporative emissions from passenger cars against real-world mobility data from two Italian provinces

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HIGHLIGHTS

- Two real-world driving patterns databases are analysed.
- The trip and parking events are characterised versus 12-hour diurnal time windows.
- The evaporative emissions have been derived for real-world driving data.
- The effectiveness of the current type approval test procedure has been evaluated.
- The evaporative emission control system could not efficiently work in real-world conditions.

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ABSTRACT

This paper presents an evaluation of the European type-approval test procedure for evaporative emissions from passenger cars based on real-world mobility data. The study relies on two large databases of driving patterns from conventional fuel vehicles collected by means of on-board GPS systems in the Italian provinces of Modena and Firenze. Approximately 28,000 vehicles were monitored, corresponding to approximately 36 million kilometres over a period of one month. The driving pattern of each vehicle was processed to derive the relation between trip length and parking duration, and the rate of occurrence of parking events against multiple evaporative cycles, defined on the basis of the type-approval test procedure as 12-hour diurnal time windows. These results are used as input for an emission simulation model, which calculates the total evaporative emissions given the characteristics of the evaporative emission control system of the vehicle and the ambient temperature conditions. The results suggest that the evaporative emission control system, fitted to the vehicles from Euro 3 step and optimised for the current type-approval test procedure, could not efficiently work under real-world conditions, resulting in evaporative emissions well above the type-approval limit, especially for small size vehicles and warm climate conditions. This calls for a revision of the type-approval test procedure in order to address real-world evaporative emissions.

1. Introduction

Evaporative emissions from vehicles are Volatile Organic Compounds (VOCs) emitted by the fuel system and other vehicle's parts (e.g. tyres, internal trim, plastic components) and not directly related to the combustion process of the fuel in the engine. These emissions depend on a number of factors, such as the size of the tank, the fuel volatility, the material used for the tank and fuel hoses, the parking duration and the ambient temperature. Among these, the main factor determining evaporative emissions is the fuel volatility combined with the variation of the fuel temperature as a consequence of ambient temperature fluctuations, solar radiation and heat sources (e.g. engine), as per Stump et al. (1990) and Rubin et al. (2006). In general, evaporative emissions occur during the operation of the vehicle (i.e. running losses), immediately after the vehicle's engine is switched off after operation (i.e. hot soaks), during the refuelling, and during vehicle diurnal parking. In particular, this last source of VOCs is considered the predominant part, as outlined in Yamada (2013).

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Nomenclature

Acronyms

CARB	California Air Resources Board
COPERT	COmputer Program to calculate Emissions from Road Transport
DVPE	Dry Vapour Pressure Equivalent
EPA	Environmental Protection Agency
EMS	Engine Management System
EUDC	Extra-Urban Driving Cycle
FID	Flame Ionization Detector
GMT	Greenwich Mean Time
GPS	Global Positioning System
GWC	Gasoline Working Capacity
LDV	Light Duty Vehicle
HDPE	High Density Poly-Ethylene
NEDC	New European Driving Cycle
OBD	On Board Diagnostics
PD	Probability Distribution
PFI	Port Fuel Injection
SUV	Sport Utility Vehicle
UDC	Urban Driving Cycle
US	United States of America
VELA	Vehicle Emission LAboratory
VOC	Volatile Organic Compound
WLTC	Worldwide Harmonised Light Vehicles Test Cycle

The current European legislation on evaporative emissions of vehicles dates back to the Council Directive 98/69/EC (European Parliament, 1998), which introduced the Euro 3 and 4 steps for Light Duty Vehicles (LDVs). As a result of the implementation of this piece of legislation, since the year 2000, gasoline vehicles for the European market have been equipped with an activated carbon canister placed on the vent of the tank. Its purpose is to trap the fuel vapours and avoid that these are released into the air. The carbon canister has a limited capacity and for this reason needs purging, therefore part of the combustion air is drawn through the canister when the vehicle is running, removing the hydrocarbons trapped in the canister which are then burned in the engine. The size of the carbon canister, the Gasoline Working Capacity (GWC) of the activated carbon and the purging strategy are key parameters affecting the efficiency of the evaporative emission control system. It is important to stress that evaporative emissions increase disproportionally when the carbon canister gets saturated as a consequence of extended parking events or insufficient purging.

Since the introduction of this directive, neither the evaporative emission standards nor the test procedure has changed. It is now considered necessary to revise the European legislation on evaporative emissions in order to improve the performance of the emission control system in real-world driving conditions, as stated in several legislative documents, such as the article 4 of the regulation (EC) No. 715/2007 (European Parliament, 2007) and the communication 2008/C 182/08 (European Parliament, 2008). According to these documents, two main issues must be addressed:

- A more effective control of evaporative emissions under real-world driving conditions. This implies that real-world efficiency and durability of the evaporative emissions control system have to be addressed.
- The impact of ethanol fuel on evaporative emissions.

An attempt to quantify real-world evaporative emissions can be found in Ross et al. (1995) and Brooks et al. (1995). These papers refer to an experimental campaign carried out in the Phoenix area with 300 vehicles tested in real-world conditions, showing that approximately 15% had evaporative emissions above 2 g. For only 20% of these high-emitting vehicles the high emissions could be ascribed to a malfunction of the evaporative emission control system whilst for the remaining 80%, i.e. approximately 12% of the fleet considered, the high evaporative emissions were due to severe ambient conditions.

The objective of this paper is to address to what extent the test conditions specified in the current European evaporative emission legislative test procedure cover typical real-world driving/parking conditions by estimating the averaged emissions per vehicle type and ambient condition (i.e. calendar month) with the simulation software COPERT (Emisia, 2013). This study relies on large datasets of real-world activity data of LDVs (i.e. approximately 28,000 vehicles equivalent to 36 million kilometres, from the Italian provinces of Modena and Firenze). These data can be useful for different studies, such as electric vehicle usability (De Gennaro et al., 2013a) and energy demand (De Gennaro et al., 2014), or in combination with chassis dyno tests to calculate on-road driving emissions (Sturm et al., 2000). The innovative contribution of this work is their use, for the first time, to evaluate the effectiveness of the evaporative emission type-approval test procedure in controlling real-world emissions, in order to provide scientific evidences and quantitative data to support the improvement of the type-approval test-procedure.

The results of the analysis show that the evaporative emission control systems used in European vehicles, which are typically designed to comply with the European legislative evaporative emission test, do not adequately cover real-world conditions and how a large share of parking events could systematically lead to emissions well above the limit set by the type-approval test procedure, mainly as a consequence of canisters not sufficiently purged.

2. Background information

2.1. European type-approval test-procedure for evaporative emissions and comparison with the US legislation

The evaporative emission test (Type IV), laid down in the Council Directive 98/69/EC (European Parliament, 1998), is designed to determine hydrocarbon evaporative emissions as a consequence of diurnal temperature fluctuation during parking and hot soaks. Hot soak emissions are usually attributed to the evaporation of the petrol in the fuel and injection system immediately after the engine is switched off. Diurnal emissions are instead the evaporative emissions occurring from a vehicle whilst it is not being operated. The European test procedure consists of the following main phases:

- test preparation (i.e. canister and vehicle conditioning);
- hot soak loss determination (i.e. hot soak test, 1-hour duration);
- diurnal loss determination (i.e. 24-hour diurnal test).

Evaporative emissions are measured using an air-tight chamber able to contain the vehicle under test. The VOCs concentration inside the chamber is monitored by means of a Flame Ionization Detector (FID) analyser. The mass emissions of hydrocarbons from the hot soak and the diurnal loss phases are added up to provide an overall result for the test. Before starting the measurement of the evaporative emissions, both the vehicle and the carbon canister have to be properly prepared according to a specific conditioning described in the legislative procedure. The carbon canister has to be loaded with butane to the breakthrough condition, defined as the operation point when 2.0 g of hydrocarbons have been emitted by the canister. As far as the vehicle is concerned, the following conditioning steps have to be carried out:

- Fuel drain and refill: after the butane loading of the canister to the breakthrough condition is completed and the canister reconnected to the fuel system, the tank is filled with test fuel at a temperature of about 287 K (14 °C) to 40 ± 2% of the tank's normal volumetric capacity.
- Preconditioning drive: within 1 h from completing the canister loading, the vehicle has to be placed on a chassis dynamometer and driven

through one Part One (i.e. Urban Driving Cycle, UDC) and two Part Two (i.e. Extra-Urban Driving Cycle, EUDC) driving cycles of Type I test (i.e. New European Driving Cycle, NEDC).
- Conditioning drive: after the completion of the pre-conditioning drive and a minimum of 12 h to maximum 36-hour soaking, the vehicle is driven further through one complete NEDC and one Part One (i.e. UDC). Therefore, the total distance driven during the preconditioning and conditioning drive equals to 33 km.

After the vehicle conditioning is completed, the actual measurement of the emissions can start:

- Hot soak test: this test simulates the condition of a vehicle parked after having been driven for a certain distance. Within 7 min from the completion of the preconditioning drive, the vehicle is placed into the measuring chamber with the engine switched off. The test lasts 60 min and the temperature must not be less than 296 K (23 °C) and more than 304 K (31 °C) during the hot soak period.
- Diurnal test: this test lasts 24 h and simulates the situation of a vehicle parked for one full day in the summer period; the temperature in the measurement chamber is varied according to a profile defined by the legislation to ideally reflect the fluctuations occurring during day and night time. The starting temperature is 20 °C whilst the maximum value is 35 °C, reached after 12 h. Then, during the subsequent 12 h the temperature slowly decreases and goes back to 20 °C.

The final result of the test is given by the sum of the emissions measured during the hot soak and diurnal test, and this is defined total evaporative emissions. The European limit for this sum is currently 2 g/test according to the Directive 70/220/EC (European Parliament, 1970) and subsequent amendments.

Despite some similarities, the European and the US legislative requirements on evaporative emissions are very different. In general the US legislation is more complete than the European one, covering all the critical factors affecting evaporative emissions. One of the main differences between the EU and the US test procedures is the duration of the diurnal test. Whilst in Europe the diurnal test lasts 24 h, in the USA there are two different diurnal tests lasting respectively 48 (twodays) and 72 (threedays) hours. The two-day diurnal test is designed to cover conditions corresponding to short distance driving and two day parking maximum, whilst the three-day diurnal test is designed to cover extended parking events. The different purpose of the two-day and three-day diurnal tests is reflected also in the conditioning procedures for both the canister and the vehicle that differ significantly. In the two-day test the canister is loaded to the breakthrough whilst in the three-day test it is loaded to complete saturation. Finally, the conditioning drive to be completed prior to starting the test is much shorter in the two-day test compared to the three-day test. Not only is the test procedure very different, but also the emission standards are much more severe in the USA. The emissions limits are 1.2 g/24 h (worst day) for the two-days and 0.95 g/24 h (worst day) for the three-day diurnal test (Delphi, 2013/14). The standards in force in California are even lower (0.5 g/test). Further details on the comparison between the European and the US legislation on the evaporative emissions can be found in (Martini et al., 2012a).

2.2. Factors influencing evaporative emissions

As stated in the Introduction section real-world evaporative emissions are the result of a combination of factors. One of the most important factors is the efficiency of the carbon canister in trapping the fuel vapours (i.e. the GWC of the activated carbon) that depends not only on the size of the canister (that is the amount of carbon) but also on the level of saturation of the activated carbon. The latter depends on the history of the vehicle and particularly on the duration of the previous parking event (i.e. quantity of fuel vapour generated) combined with the length, speed and duration of the previous trip (i.e. total purging volume drawn through the canister, active purging).

In addition to the active purging performed during vehicle operation, the canister can be also passively purged during parking events with a decreasing ambient temperature (e.g. overnight parking). In this case air flows into the tank to compensate the decreasing of the volume of the fuel vapours purging at the same time in the canister. However the passive purging has a relatively small influence compared to the active purging. Furthermore the adsorption efficiency of the activated carbon can decrease over time due to ageing of the carbon itself or to the formation of a hydrocarbon heel that cannot be removed by purging.

According to the current legislative test procedure (see Section 2.1), the carbon canister is purged during the vehicle preconditioning and conditioning steps (i.e. accounting for a total driving distance of 33 km).

Recent investigations (Pierson et al., 1996; McLaren et al., 1996) show that the purging strategy adopted in European vehicles is in general optimised for the test procedure, and in some passenger cars the canister is not purged efficiently over the low speed part of the NEDC cycle which should represent urban driving (Martini et al., 2012). Moreover, real-world activity data analyses show that the typical trip length is much shorter than 33 km, especially in urban areas (De Gennaro et al., 2013b; Paffumi et al., 2014). From the above considerations it is easy to conclude that the most critical conditions for real-world evaporative emissions occur in urban areas, where the vehicle is typically driven for very short distances at low speeds and then can be left parked for long time under solar radiation (i.e. warm climate conditions).

Fuel permeation represents another major source of evaporative emissions from passenger cars and it strictly depends on the material used for the fuel tank and lines. Standard mono-layers High Density Poly-Ethylene (HDPE) tanks, still adopted in about 35% of the vehicles sold in Europe according to Association of plastic tank manufacturers (2013), are characterised by higher permeation rates compared to multilayer or metal fuel tanks, typically used in the US, where stricter emission limits are applied. In addition fuel volatility is also important to determine the amount of vapours generated at a given temperature. The reference fuel prescribed by the current European legislation for the evaporative emission test must have a maximum Dry Vapour Pressure Equivalent (DVPE) of 60 kPa (European Parliament, 1998). Fuels with a higher vapour pressure, as in the case of fuel containing ethanol, may lead to faster saturation of the canister and higher real-world evaporative emissions. The European directive 2009/28/EC on the promotion of renewable fuels (European Parliament, 2009) set the objective of 10% coverage of the transport fuel market with renewable energy sources, including biofuels by 2020. Bioethanol is one of the main options to achieve this target, but it has a significant influence on both exhaust and evaporative emissions of petrol passenger cars.

If ethanol is splash blended into a standard gasoline at low levels (i.e. 5–10%), the vapour pressure in many cases significantly increases (i.e. approximately by 6–7 kPa) and larger volumes of vapour are generated in the tank. The current European fuel Directive requires pure gasoline and ethanol/gasoline blends to meet the same vapour pressure specification (60 kPa for the summer grade gasoline) and allows splash blending only upon a derogation to be requested and justified by Member States. However, even in absence of a request for derogation, where gasoline with and without ethanol coexist in the same area, the vapour pressure of fuel will inevitably increase as a result of accidental mixing of these fuels in the tank (i.e. commingling effect). This may lead to a faster saturation of the canister and consequently to higher emission values, since the certification test is carried out with a fuel containing 5% ethanol but with a maximum vapour pressure of 60 kPa whilst in the real world the fuel in the tank may reach values around 67–68 kPa. In addition ethanol also increases the permeation rate of fuel through plastic materials, as those of which the tank is made, and may also reduce the GWC of the carbon canister due to the polarity of its molecule.

These issues have been addressed in literature by Furey and King (1980) and Poulopoulos et al. (2001) and, in response to this, the US Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) developed specific measures in order to cope with them. These measures are still missing in Europe and for a forward looking review of the test procedure these aspects have to be taken into account. As far as the EU legislation is considered, the reference fuel for emission testing at vehicle type approval must contain 5% ethanol. However, the effect of ethanol on fuel permeation is not instantaneous and it can take up to few tens of weeks to achieve a stable permeation rate. In other words, if the ethanol containing fuel is put in the cars just at the moment of the evaporative test, the effect on fuel permeation will be strongly underestimated.

Ethanol influence on evaporative emissions is only partially addressed in this work, by considering the increased permeation rate of the fuel tank material, whilst the commingling effect is not considered.

3. Methodology

The methodology developed in this study is based on the three following steps:

1) Derivation of real-world typical trip lengths and parking duration distributions from the activity databases.
2) Evaluation of the correlation of these real-world parking events with the legislative test in terms of parking duration (24 h with 12 h of increasing temperature). To this purpose diurnal time windows relevant for evaporative emissions have been defined, on the basis of the solar radiation windows in May (i.e. month in which the data acquisition campaign was carried out).
3) Simulation with COPERT (Emisia, 2013) of the evaporative emissions on the basis of the results of step 2. The simulation set-up and model were based on the experimental results from the VELA laboratories (Mellios et al., 2009), partially presented in Section 3.3.

3.1. Description of the activity databases and mobility analysis results

Two large vehicles activity data sets of two Italian mid-sized provinces Modena and Firenze were purchased from the private company Octo Telematics (Octo Telematics Italia S.r.l., 2013). These sets of data were extracted from the Octo Telematics data pool according to specific criteria in order to obtain a sample representative of urban driving conditions in those geographical areas. The vehicle activity data were acquired by means of GPS devices installed on the vehicles and connected via GSM to a remote storage unit. This is becoming more and more popular in some countries due to the possibility to pay reduced vehicle insurance fees. The acquisition devices anonymously records: time, GPS position coordinates, engine status, instantaneous speed and cumulative distance and this enables to reconstruct in detail the driving pattern of each of the monitored vehicles.

The two data sets analysed cover a period of one month (i.e. May 2011) and were initially referred to 52,834 vehicles for Modena (12.0% of the total fleet of the province) and 40,459 vehicles for Firenze (5.9% of the total fleet of the province). As mentioned above, urban driving conditions represent the most critical conditions for evaporative emissions. Therefore only the cars showing a predominant urban use, defined as the majority of the trips (i.e. more than 50%) occurring within the province border, were considered in this analysis. As a consequence, the final data sets included 16,223 vehicles for Modena (30.7% of the original size, 3.7% of the fleet in the province) and 12,422 vehicles for Firenze (30.7% of the original size, 1.82% of the fleet in the province). The cumulative mileage analysed amounts to 15.0 million km and 20.6 million km, for Modena and Firenze respectively, corresponding to approximately 16.0 million and 32.0 million records and 2.64 million and 1.87 million trip and parking events, as summarised in Table 1.

The activity data analysed are referred to the month of May and have been assumed to be representative of the driving behaviour also for the other months of the year. This means that in this analysis the seasonal variation of the driving habits, which however is assumed to be rather limited even for different countries according to Marconi et al. (2004), has not been considered. Moreover the data refers to specific areas of the provinces of Modena and Firenze, characterised by homogeneous social and wealth conditions, and therefore, with similar mobility demand and driving behaviours.

It must be also considered that evaporative emissions strongly depends on climate conditions and therefore Southern Europe countries, like Italy, represent the worst cases. The databases have been analysed by means of in-house built scripts in MATLAB® (Mathworks Inc., 2012) according to the procedure described in De Gennaro et al. (2013b) and Paffumi et al. (2014), in order to characterise the urban mobility in the analysed areas and derive the rate of occurrence of the evaporative cycles in real-world conditions.

3.1.1. Mobility results

Fig. 1 provides the percentage of the total fleet which is in motion at the same time during week days against time. Time data are averaged on a second basis over the total period of analysis (i.e. May 2011). Three traffic peaks can be seen from Monday till Friday for both provinces, in the morning (approximately at 7.30), in mid-day (approximately at 12.00) and in the evening (approximately at 18.30). Instead, two peaks are found in the weekend approximately at 12.00 and at 19.00. The mobility patterns are similar for both databases and are periodically repeated during the week. The fleet share in motion at the same time never exceeds 11.72% for Modena and 10.36% for Firenze, with a mean value of 4.29% for Modena and 4.47% for Firenze. The remaining percentage to 100% in Fig. 1 represents the fleet share parked during the week. More than 90% of vehicles are parked at any given hour of the average day and in the month this value never drops below 85%.

Fig. 2 shows the trip length and the parking duration for the vehicles for the two provinces against time, based on second-average over the total period of analysis. The results show that the mean trip length is between 5 and 20 km, whilst the average parking duration is between 2 and 12 h (daily and nightly values respectively). This suggests that average trip and parking events occurring during the night are typically longer than those occurring during day time.

Fig. 3 shows the Probability Distribution (PD) histograms of the number of trips, cumulative trip length and cumulative parking duration (given as percentage of the total), aggregated per day and per week. The results are given for the province of Modena from (a) to (f) and for the province of Firenze from (g) to (l). These distributions show that more than half of the vehicles of the sample are driven for less than 6 trips and 20 km per day, and 30 trips and 200 km per week, being parked for more than 90% of the time. The time-dependent results depicted in Fig. 2 and the probability results depicted in Fig. 3 show that most of the trips are much shorter than the 33 km conditioning drive prescribed by the type-approval test for evaporative emissions.

Table 1
Overview of the analysed data for the provinces of Modena and Firenze.

	Analysed sample (no. of vehicles)	Number of analysed records [$\cdot 10^6$]	Analysed km [$\cdot 10^6$]	Number of analysed events [$\cdot 10^6$]
Province of Modena	16,223	15.998	14.98	2.64
Province of Firenze	12,422	32.008	20.66	1.87

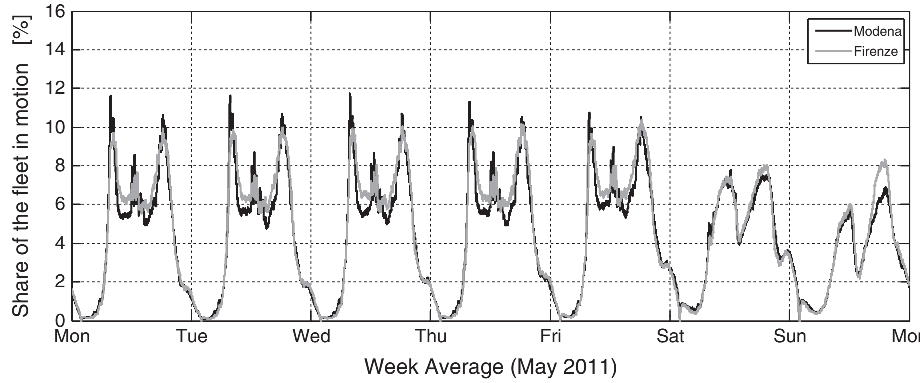

Fig. 1. Averaged percentage fleet share in motion at the same time, averaged over the week for Modena (black) and Firenze (grey).

This implies that in many vehicles the carbon canister is not properly purged in real-world driving conditions. However the driving distances have to be evaluated in combination with the duration of the parking in order to estimate the real carbon canister saturation level achieved during each parking event. This aspect is addressed in the next section.

3.1.2. Correlation between the trip length and the parking duration

In order to assess how real driving conditions impact on real-world evaporative emissions, the sequence of trips and parking events of the vehicles must be considered for determining the saturation level of the carbon canister at the beginning of each parking event. In this analysis each trip is considered as an event during which the carbon canister is totally or partially purged (according to the purging strategy implemented and the driving length). On the other hand during each parking event the carbon canister is loaded to a certain level that depends on the parking duration and the ambient conditions.

The results derived from the analysis of the activity data highlight an inverse relation between the trip length and the parking duration, showing that long trips are mostly associated to short parking durations and vice versa. Fig. 4 shows the cloud distribution of the parking duration versus the trip length and hour of the day for the 2.64 million parking events of the province of Modena and 1.87 million events of the province of Firenze. Each dot represents an event. Although these pictures only provide a qualitative representation of the distribution of the events on these axes, the inverse proportionality between trip length and parking duration mentioned above is well visible. With respect to the parking duration versus the daily hours, we find an almost uniform distribution, with events accumulated in striped-like clusters around the multiples of 24 h (vehicles parked for several days).

The quantitative representation of the clouds is provided in the tables included in the Supplementary material (from Tables S1 to S4) where cross-probabilities of the trip and parking events are given, normalised over the total number of the events considered. Each trip distance is associated to the parking event that occurs immediately after. For example in Table S1 the first box in the left-top corner indicates that 36.3% of the events are a combination of a trip length

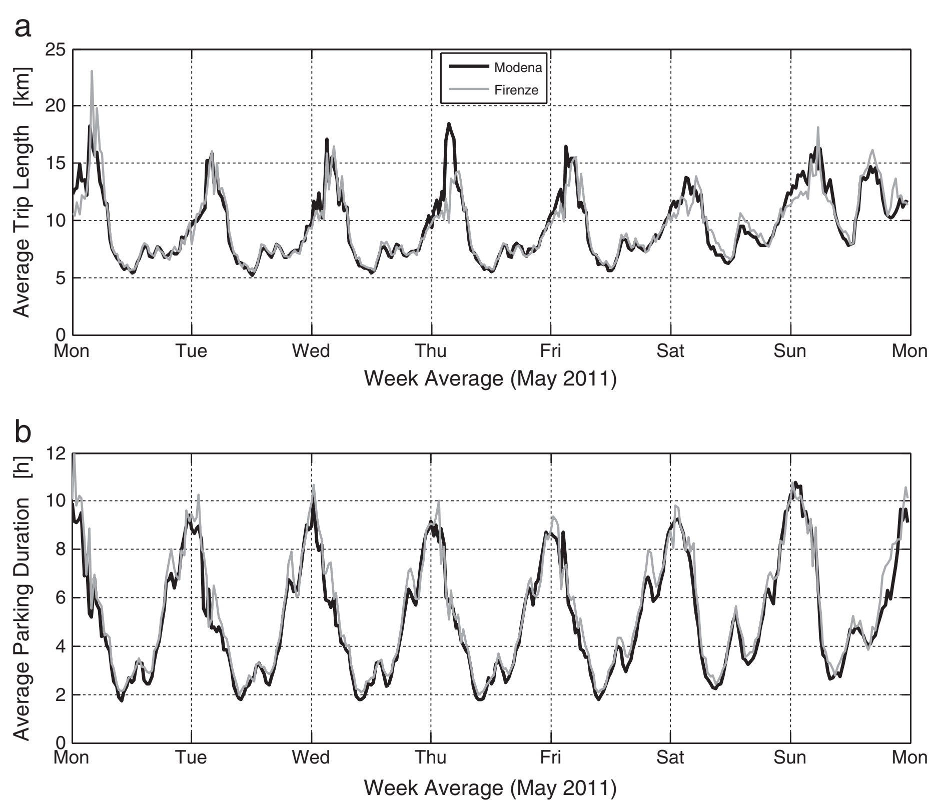

Fig. 2. Average trip length (a) and parking duration (b). Averaged second-by-second values over the analysed period for the vehicles in motion, Modena (black) vs. Firenze (grey).

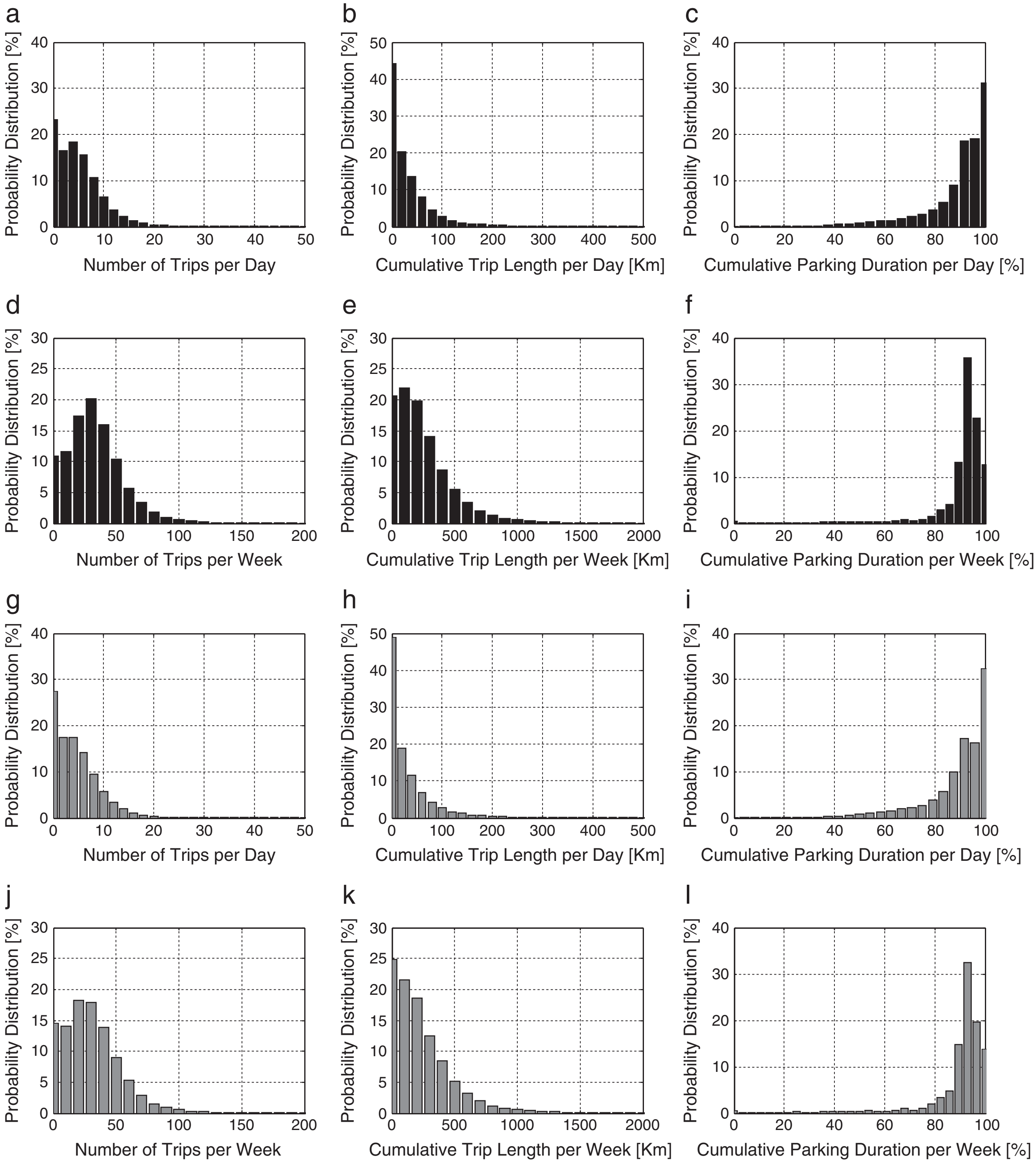

Fig. 3. PD histograms of the number of trips, cumulative trip length and cumulative parking duration per day and per week for Modena, black bars from (a) to (f), and Firenze, grey bars from (g) to (l). Results refer to the complete fleet.

between 0 and 5 km followed by a parking event with a duration between 0 and 1 h. The values integrated over the columns and the rows are respectively given in the last row and last column of each table and represent the PDs of the total occurrence of the given events. This holds for all the tables.

The distributions of the duration of the parking events and length of the trips for each vehicle in the databases have been also derived in order to evaluate the total rate of occurrences of these events per vehicle. This enabled to investigate if some vehicles in the databases are likely to bias the aggregated results (e.g. a vehicle which does a large number of very short trips, being alone the major responsible of an event of that kind). This analysis, not reported here for brevity, shows that the results are not altered by this effect.

3.2. Parking events and trip lengths versus evaporative cycles

In order to assess to what extent the legislative test procedure covers real-world driving/parking conditions, the analysis has been focused on parking events that can be considered similar to those simulated with the legislative test procedure (24 h duration, with 12 h of increasing

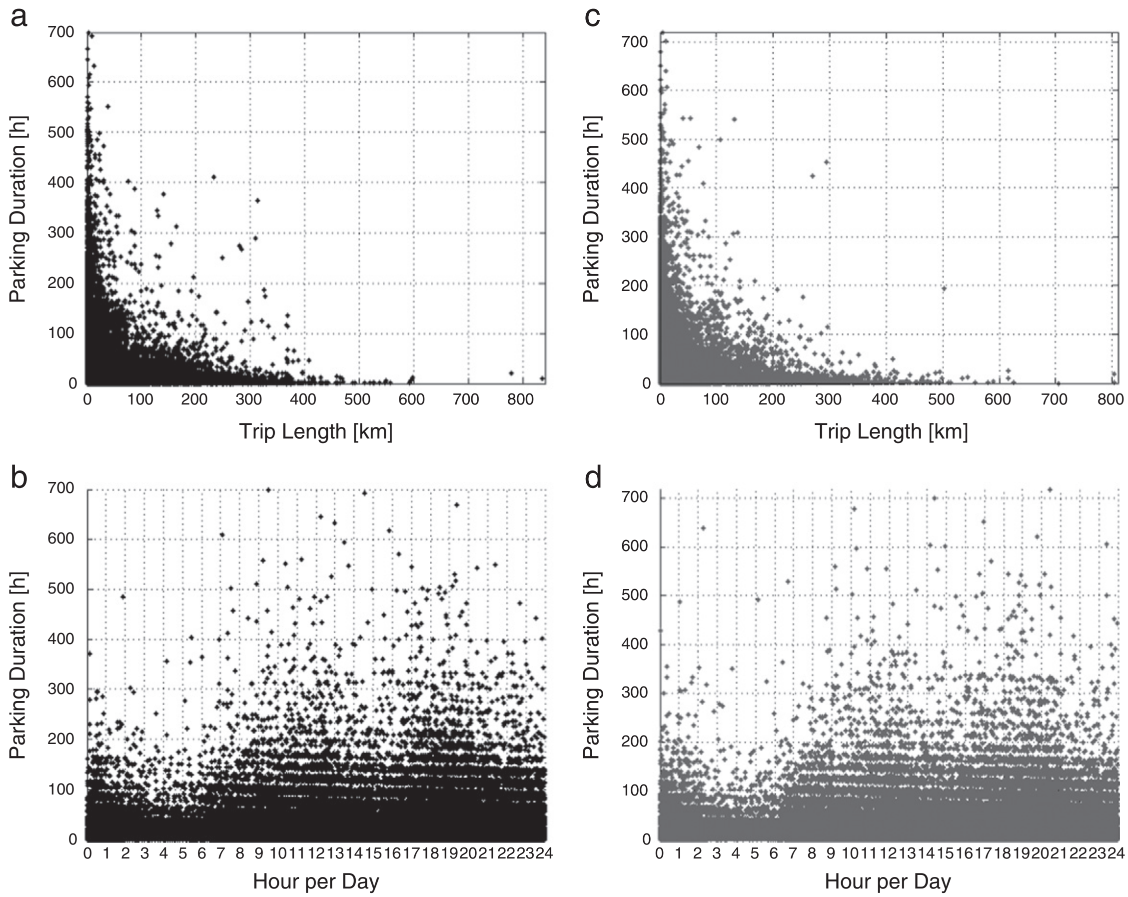

Fig. 4. Cloud distribution of parking duration vs. trip distance and hour of the day for Modena, black dots in picture (a) and (b), and Firenze, grey dots in picture (c) to (d). Results refer to the totality of the fleet.

temperature). To this purpose the diurnal time window relevant for evaporative emissions has been defined on the basis of the solar radiation windows. Considering that the analysed activity datasets refer to the month of May, an average sunrise time approximately at 05.50 in the morning and an average sunset time approximately at 20.20 (values of the 15th of May for Italy, GMT + 2 h) have been assumed. Typical temperature profiles for that period show that the temperature increases approximately from 6.00 to 18.00, period that is here defined as evaporative cycle.

The duration and the starting time of each parking event included in the databases have been crossed with this diurnal time window to quantify the number of evaporative cycles (as defined above) to which each car is exposed. The result has been rounded to an integer number, meaning that a parking event which shows a partial overlapping with one or more evaporative cycles is rounded to the closest integer. For instance let us consider a parking event from 8.00 to 12.00. The event lasts for 4 h, with a 4 h overlapping with the evaporative cycle which extends from 6.00 to 18.00. However its duration versus the duration of the cycle (i.e. overlap-to-cycle ratio $= 4/12 = 0.33$) is below 0.5, therefore the event is marked as “0-cycle”. On the other hand let us consider a parking event from 10.00 to 24.00. The event lasts for 14 h, with 8 h overlap with the cycle. The overlap-to-cycle ratio is 0.66; therefore the event is marked as “1-cycle”. Finally let us consider the parking event from 10.00 of a day to 17.00 of the day after. It overlaps 8 h with the cycle in the first day and 11 h with the cycle in the second day. The total overlap time is 19 h, resulting in an overlap-to-cycle ratio of 1.58, rounded to “2-cycles”. This overlap-to-cycle ratio is evaluated for all the parking events in the database, characterising the occurrence of full evaporative cycles for each vehicle parking event.

It must be highlighted that if it is true that this round-off of the data approximates the events from 0.51 overlap-to-cycle ratio on to one full evaporative cycle, overestimating their diurnal exposure, it is also true that those events characterised by an overlap-to-cycle ratio up to 1.49 are approximated to one full evaporative cycle as well underestimating in this case their exposure. These approximations compensate each other, being the parking duration distribution rather flat from 6 h on, as shown in Tables S1 and S3 (see Supplementary material).

All the parking events marked as “0-cycle” are assumed to be covered by the type approval test procedure and filtered out of the database. These are parking events with either a too short duration (corresponding to small amount of generated vapours) or that happen mostly during the night, even though with a relatively long duration. The overnight events are typically characterised by the passive purging of the carbon canister, due to the decrease of the temperature.

The parking events that are filtered-out being marked as “0-cycle” are approximately 90% of the total parking events. The events, marked as “1-cycle”, are about 0.252 million for the province of Modena and 0.193 million for the provinces of Firenze (Table 2).

Although the large majority of events are considered well covered by the existing test procedure, the remaining 10% of events shows a non-negligible rate of occurrence per vehicle as shown in Table 2. On average, in the Modena province, each vehicle is left parked for one, two and three evaporative cycles for approximately 8, 6 and 1 times per month respectively. These values become 11, 10 and 5 times per month in the Firenze province. Long parking events, involving 6 evaporative cycle on, have a very low probability to occur (i.e. less than one event per vehicle in one month). However these events are responsible of evaporative emissions of two orders of magnitude higher than the legislation limit (as shown later on in Section 4) and they must be considered for the evaporative emission assessment. The differences of the average occurrences of evaporative cycles reported in Table 2 between the provinces of Modena and Firenze can be presumably ascribed to the impact of use of public transportation on mobility habits of people.

Tables 3 and 4 show the cross-probability of the occurrence of a given number of evaporative cycles against the length of the trip before the parking event. In both provinces about 50% of the parking events correspond to one evaporative cycle, but the large majority of these events is preceded by a trip length well below the 33 km conditioning drive prescribed by the type-approval test procedure. Longer parking duration that involves more evaporative cycles has less probability to occur, and approximately 1.5% of parking events last more than 6 days.

3.3. Experimental tests on evaporative emissions

The typical purging strategy of passenger cars available on the European market has been investigated at the Vehicle Emission LAboratory (VELA) of the Joint Research Centre of the European Commission in Ispra (Italy) with the experimental campaign described in Martini et al. (2012a), involving 5 different vehicles equipped with Port Fuel Injection (PFI) gasoline engines, Table 5. Here only a summary of the results is presented, focusing on the influence of the driving distance and purging strategy on the cumulative purging volume and therefore on the carbon canister loading after driving.

Vehicles 1 and 2 were popular Euro 4 small passenger cars, with 1.3 and 1.2 l engine respectively, whereas vehicle 3 was a medium class Euro 4 passenger car equipped with a 1.8 l engine. Vehicle 5 was a small Euro 5 passenger car, with a downsized 0.9 l engine, whereas vehicle 4 was a large Sport Utility Vehicle (SUV) manufactured in the USA and imported in Europe. It is important to notice that the evaporative control system of vehicle 4 is designed to comply with the US legislation.

The vehicles 1, 2, 3 and 4 were tested for evaporative emissions and the second-by-second purging flow rate was recorded both over the pre-conditioning and conditioning drive cycles prescribed by the relevant legislative test procedure (European Parliament, 1998) (see Section 2.1). Instead vehicle 5 was tested only for exhaust emissions and therefore the purging flow rate was recorded over the NEDC and over the new worldwide harmonised test cycle for light duty vehicles (WLTC, draft version).

The results are given in Fig. 5, where the instantaneous purging flow rate and cumulative purging volume over the pre-conditioning and conditioning driving cycles are shown. It appears that the purging strategy of typical European passenger cars can vary significantly from model to model. In general, as expected, the purging flow rates recorded over the urban part of the cycle are significantly lower compared to those measured over the extra-urban part. However, in some cases, the flow rates over the urban part are unacceptably too low (e.g. vehicle 3 and to a lesser extent vehicle 2). Obviously, although the legislative evaporative emission standard is met, the different purging strategy may lead to different level of canister loading in real-world driving conditions, resulting, in some cases, in uncontrolled evaporative emissions especially when the vehicle is driven in urban areas.

Vehicle 4 (a large SUV for the US market and whose evaporative emission control system is designed to comply with the US legislation) has instead the highest purging flow rate and this seems to be less dependent on the cycle phase and on the driving speed. If it is true that this can be partially attributed to the large displacement of the engine (i.e. higher purging flow rate), it is also true that the US legislative requirements force the adoption of a more aggressive purging strategy when compared to the EU procedure. The 48-hour diurnal test required by the US legislation has been designed with the main objective of covering the urban critical conditions mentioned above. The driving time/distance available for canister purging after the canister loading to the breakthrough condition is in fact much shorter than the total conditioning drive prescribed by the European test procedure, resulting in a more aggressive purging strategy with approximately 200 l of volume flow air just after the UDC cycle (well above the other vehicles).

3.4. COPERT set-up for the evaporative emission simulation

The COPERT software (Emisia, 2013) was used to estimate the total evaporative emissions from passenger cars based on the driving/parking patterns derived from the activity data described above. The evaporative emission model implemented in COPERT is described in

Table 3
Cross-probability [%] of the occurrence of the 12-hour evaporative cycles (horizontal) vs. trip length of the previous trip [km] (vertical) for the Modena database.

12 h evap. cycles / Trip [km]	1	2	3	4	5	6–30	Σ ↓
0–1	9.685	7.095	1.614	0.542	0.211	0.354	19.500
1–2	7.088	4.887	0.968	0.280	0.116	0.151	13.488
2–3	4.908	3.472	0.634	0.204	0.083	0.112	9.413
3–4	3.739	2.703	0.495	0.144	0.053	0.085	7.219
4–5	2.971	2.235	0.393	0.117	0.050	0.065	5.830
5–6	2.595	1.887	0.356	0.093	0.039	0.062	5.032
6–7	2.166	1.501	0.271	0.078	0.029	0.044	4.088
7–8	1.770	1.288	0.236	0.068	0.029	0.040	3.430
8–9	1.533	1.076	0.189	0.059	0.020	0.028	2.905
9–10	1.276	1.000	0.171	0.051	0.018	0.032	2.548
10–12	2.236	1.653	0.310	0.104	0.038	0.040	4.381
12–14	1.938	1.423	0.256	0.079	0.031	0.043	3.769
14–16	1.494	1.172	0.210	0.061	0.025	0.036	2.999
16–18	1.185	0.907	0.167	0.058	0.016	0.030	2.363
18–20	0.917	0.741	0.118	0.036	0.016	0.024	1.853
20–30	2.723	2.212	0.391	0.114	0.048	0.072	5.560
30–785	2.442	2.330	0.497	0.161	0.073	0.119	5.622
Σ →	50.665	37.579	7.276	2.249	0.894	1.337	100.000

Table 2
Summary of the results of the analysis of the parking events versus the evaporative cycles.

	Analysed Vehicles	Total parking events [$\cdot 10^6$]	Parking events ≥ 12 h [$\cdot 10^6$] – (% of the total)
Province of Modena	16,223	2.642	0.252 – (9.55%)
Province of Firenze	12,422	1.870	0.193 – (10.26%)

12 h evap. cycles / Database	1	2	3	4	5	6	7	8	9	10	11–31
	Average occurrence of evaporative cycles per vehicle in the month										
Province of Modena	7.89	5.85	1.13	0.35	0.14	0.08	0.05	0.03	0.01	0.01	0.03
Province of Firenze	11.27	10.15	5.46	0.88	0.70	0.30	0.22	0.10	0.10	0.05	0.24

Table 4
Cross-probability [%] of the occurrence of the 12 -hour evaporative cycles (horizontal) vs. trip length of the previous trip [km] (vertical) for the Firenze database.

12 h evap. cycles / Trip [km]	1	2	3	4	5	6–31	Σ ↓
0–1	8.571	7.326	1.811	0.627	0.290	0.486	19.111
1–2	6.726	5.073	1.028	0.318	0.131	0.204	13.479
2–3	4.955	3.736	0.785	0.240	0.116	0.141	9.972
3–4	3.768	2.966	0.570	0.180	0.075	0.111	7.670
4–5	2.939	2.258	0.429	0.137	0.056	0.088	5.907
5–6	2.404	2.014	0.334	0.119	0.046	0.069	4.986
6–7	2.052	1.629	0.305	0.110	0.039	0.061	4.196
7–8	1.757	1.377	0.297	0.096	0.039	0.061	3.627
8–9	1.515	1.195	0.224	0.081	0.029	0.043	3.087
9–10	1.244	1.038	0.203	0.058	0.027	0.028	2.597
10–12	2.124	1.706	0.305	0.107	0.042	0.058	4.341
12–14	1.655	1.306	0.227	0.090	0.041	0.050	3.369
14–16	1.248	1.014	0.205	0.066	0.026	0.043	2.602
16–18	0.978	0.821	0.153	0.055	0.020	0.029	2.056
18–20	0.733	0.595	0.104	0.039	0.010	0.031	1.512
20–30	2.225	1.815	0.357	0.132	0.051	0.084	4.663
30–805	3.057	2.685	0.608	0.211	0.090	0.175	6.826
Σ →	47.951	38.553	7.944	2.666	1.128	1.758	100.000

Mellios et al. (2009) and it is based on experimental tests, partially presented in Section 3.3. The model requires as input:

- Carbon canister size. Different sizes were assumed, in order to represent small, medium and large size passenger cars. The values were set to 0.8 l for the small size vehicles, 1 l for the medium size vehicles and 1.5 l for the large size vehicles.
- Fleet composition. The fleet composition for Italy was based on the data available from TREMOVE, an impact assessment model widely used in Europe to simulate the effects of different transport policy options on emissions and costs (University of Thessaloniki, 2008). It includes data on the circulating fleet in the EU28 countries plus Norway, Switzerland and Turkey. According to these data, the Italian fleet of LDVs amounts to approximately 37.9 million vehicles in 2011, with approximately 4.4 million vehicles classified as pre-Euro, 2.8 million vehicles classified as Euro 1, 6.7 million vehicles as Euro 2, 7.5 million vehicles as Euro 3, 10.8 million vehicles as Euro 4 and 5.7 million vehicles as Euro 5. Summing up the number of vehicles marketed after the introduction of the current legislation for evaporative emissions (i.e. Euro 3), it can be estimated that approximately 24.0 million passenger cars in Italy (corresponding to 63.3% of the fleet) are equipped with an evaporative emission control system. Therefore we have restricted our evaporative emission simulations to this fleet share, which is associated to approximately 74.6% of the total 2011 mileage of the Italian fleet.
- Parking and trip distribution. The distributions of the parking events in the evaporative cycles from the activity data analysis provided in Tables 3 and 4 have been used as input for the calculations. The evaporative cycles as defined in section 3.2 (i.e. month of May) have been assumed for all the year. This constitutes a limitation of the current analysis; however, being the evaporative emission model mainly influenced by the maximum and minimum temperature in the day rather than by the diurnal time window (as discussed below), the deviation introduced on the total evaporative emission results can be considered negligible. We would like to add a further clarification here, in order to improve the interpretation of the results given below. In order to better estimate the canister saturation status at the beginning of a parking event, the distance driven prior to each parking is considered. A trip distribution is introduced in the model and a purge volume per trip is calculated.
- Purge rate. Two purge rates are used to calculate the purge volume: 9.66 l/km for small size cars and 16.68 l/km for medium and large size cars. These values are assumed constant in time, even though the experiments show that they depend on the purging strategy of the vehicle. Fig. 5 shows a lower purging rate at lower speed (i.e. UDC phase of the cycle) to increase then to higher values at high speed (i.e. EUDC phase of the cycle). Assuming a constant value overestimates the purging rate at a lower speed whilst underestimates it at a higher speed, leading to conservative evaluations. The GWC of the carbon canister (i.e. amount of VOCs which the canister is able to trap) is then calculated for each trip prior to a parking event.
- Fuel permeation rate and effect of the ethanol. Based on data provided by the European association of plastic tank manufacturers (Association of plastic tank manufacturers, 2013), the permeation emissions rate of the fuel tank was set to 0.9 g/day for the fluorinated mono-layer tank (mounted on 35% of the vehicles) and to 0.5 g/day for the multi-layer tanks (mounted on 65% the vehicles). These values are derived from the base rates of 0.6 and 0.2 g/day increased by 0.3 g/day to account for the effects of ethanol (Section 2.2). No further effects (e.g. fuel vapour increase and commingling effects) are considered.
- Durability. In order to estimate the deterioration of the canister performance with ageing, data derived from an in-use compliance testing programme, carried out by the Swedish Transport Administration (Johansson and Schmidt, 2009a), were used. This study suggested that deterioration of efficiency of the activated carbon can be mainly ascribed to the presence of ethanol in the gasoline, very popular in Sweden. In this analysis the efficiency of the activated carbon is set to decrease by 1% every 8000 km for small cars (i.e. approximately 20% drop over the lifetime) and by 1% every 32,000 km for medium and large cars (i.e. approximately 5% drop over vehicle lifetime). However in other countries, where ethanol is not so widely used, the deterioration rates may be lower.
- Ambient temperature. The averaged ambient temperatures per month as reported in Table 6 have been considered for the simulations in the provinces of Modena and Firenze respectively. The model only considers minimum and maximum temperatures.

Table 5
Vehicles tested for evaporative emissions.

	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5
Emission level	Euro 4	Euro 4	Euro 4	Euro 4	Euro 5
Engine	Gasoline	Gasoline	Gasoline	Gasoline	Gasoline
Displacement [cm^3]	1360	1197	1794	6063	875
Max. power [kW]	55	47	88	313	62.5
Injection system	PFI	PFI	PFI	PFI	PFI

4. Results of the evaporative emission simulations

The COPERT model results for real-world total evaporative emissions have been compared to the type-approval limit of 2 g/test. Figs. 6 and 7 show the total evaporative emissions defined as the sum of the following contributions:

- hot soak emissions, assumed equal to 0.1 g/test;
- fuel permeation emissions, assumed as weighted average between mono and multi-layer tanks, plus the effect of the ethanol (as described in Section 3.4).
- breathing emissions, as variable contribution from the vapours generated in the fuel tank, depending on the parking duration and trip length before the parking.

The results are given for the small (a), medium (b) and large (c) size vehicle over different trip lengths before a parking of one evaporative cycle for the province of Modena and Firenze (left scale). The bars report the absolute values (i.e. not cumulative quantities) and refer to a single vehicle. The bolded dashed line indicates the 2 g threshold set by legislation, and the values are given per each month of the year in grey scale.

In general it can be noticed that the emissions depend on the vehicle size; the larger the vehicle the lower the emissions. Of course they also

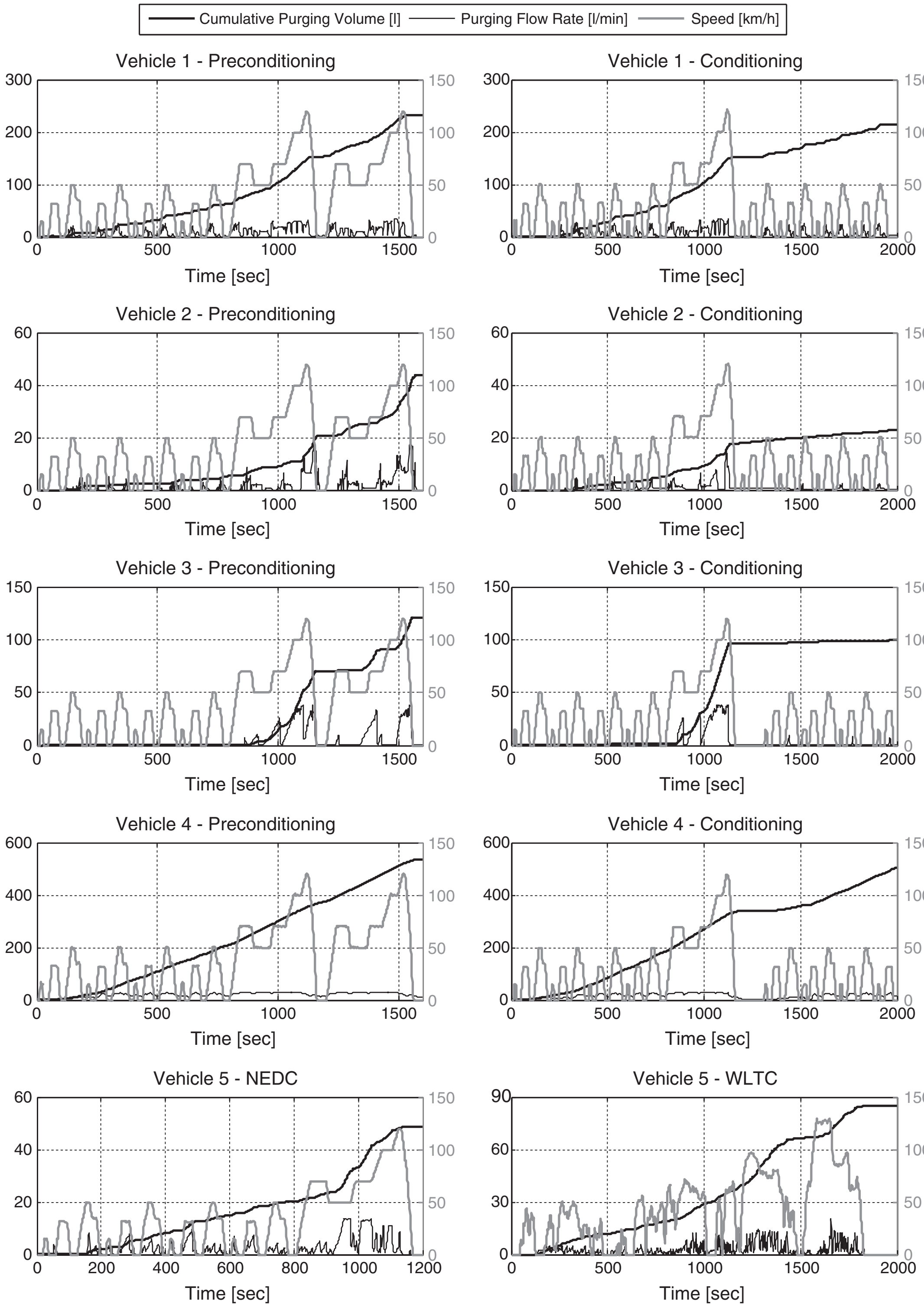

Fig. 5. Instantaneous purging flow rate [l/min] and cumulative purging volume [l] over the preconditioning (i.e. NEDC + EUDC, left picture) and conditioning (i.e. NEDC + UDC, right picture) drive cycles for the tested vehicles reported in Table 5 (from vehicle 1 to vehicle 5, from top to bottom). Black curves refer to left scale, grey curve refers to right scale. Legend at the top of the figure.

Table 6
Maximum and minimum temperatures [°C] for the province of Modena and Firenze.

[°C]		Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Modena	Min.	−1.5	0.8	3.9	7.6	11.8	15.6	18.2	17.9	14.8	10.1	4.3	−0.3
	Max.	4.8	8.2	13.4	17.8	22.7	26.8	29.9	29.2	25.3	18.9	11.1	5.9
Firenze	Min.	0.6	2.8	3.9	6.7	10.6	13.9	15.6	15.6	13.9	8.9	5.6	1.7
	Max.	8.9	10.6	13.9	17.8	22.8	26.7	30.0	30.0	25.6	20.0	13.9	10.0

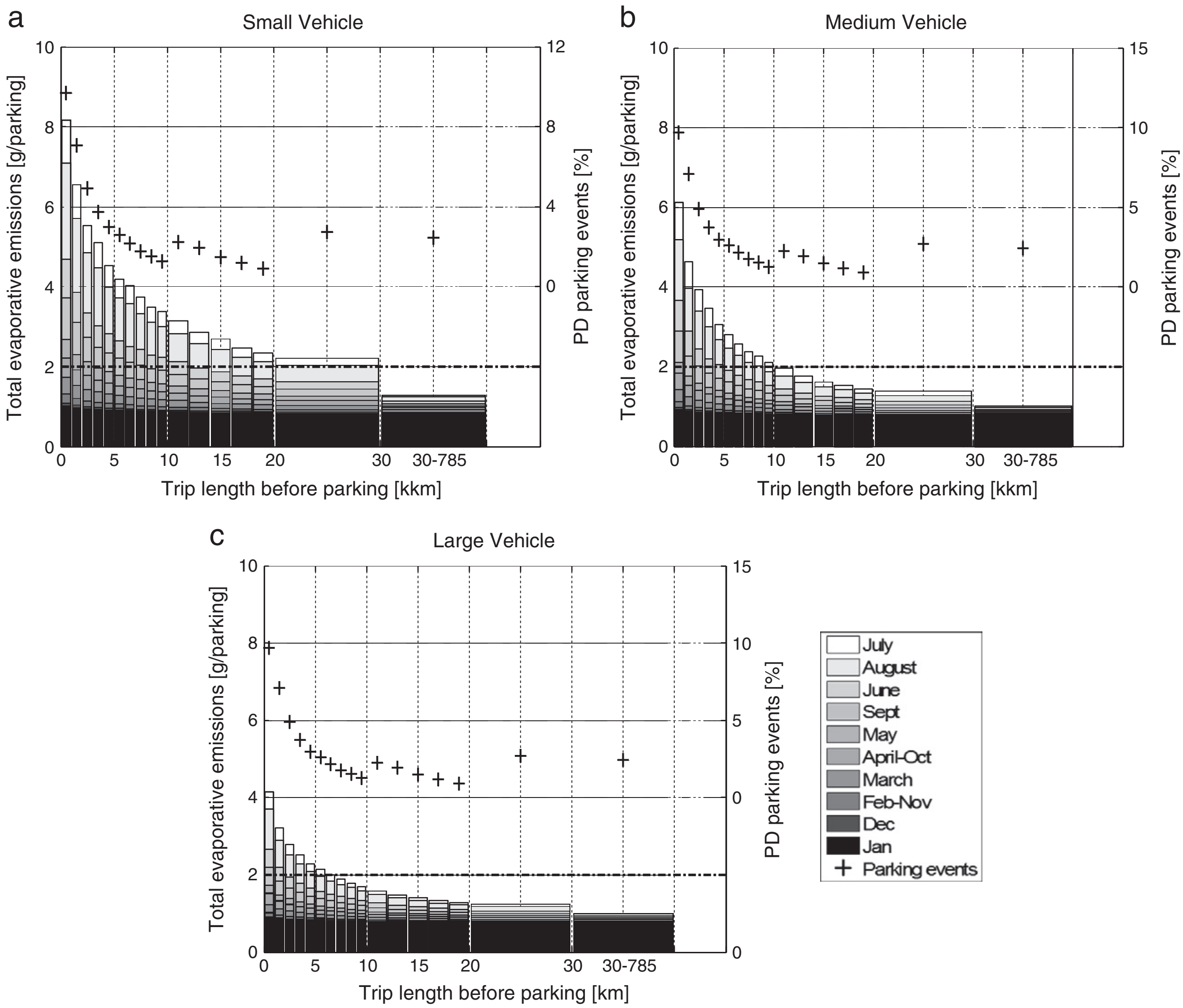

Fig. 6. Total evaporative emission distribution for the small (a), medium (b) and large size (c) over different trip lengths before a parking of one evaporative cycle (left scale). The bars report the absolute values, not cumulative quantities. PD of the parking events (right scale). Province of Modena.

depend on the ambient temperature: the warmer the temperature, the higher the emissions. Note that in Modena the highest total evaporative emissions are estimated to occur in July, whilst in August for Florence, due to the difference in ambient temperature (see Table 6).

Considering the length of the trip, the results show that trips below 10 km for the small size, 4 km for the medium size and 2 km for the large size vehicle result in evaporative emissions above the threshold limit from June to August for a parking corresponding to one evaporative cycle, whilst considering longer trip lengths (>30 km, >10 km and >6 km respectively for the small, medium and large size vehicle), the evaporative emissions are lower than the legislative limit, regardless the month considered. This implies that the purging strategy, which depends very much on the length of the trip, plays a major role in determining total evaporative emissions especially during the warmer months. The PD of the parking events versus the trip length is reported on the right scale of these figures (i.e. first column of Tables 3 and 4). We observe that parking events after short trips have higher probability to occur in the databases and, summing up this cross-probability, we derive approximately 95% of the events are below 30 km, 70% below 10 km and 55% below 6 km, and only 2.5% of the parking events are associated to a trip length longer than 33 km conditioning drive.

Considering the composition and the different market segments of the Italian circulating fleet (referred to the year 2011 (De Gennaro et al., 2013a), according to the market segmentation provided in (European Commission, 1999)), we derive that approximately 37.6% of the fleet is made by small size vehicles (i.e. market segments A and B), 29.1% by medium size vehicles (i.e. market segments C and D), and only 4.9% of the fleet by large size vehicles (i.e. segments E, F, M and J). Therefore combining these shares with the cumulative trip share mentioned above (i.e. 95%, 70% and 55%), we derive that more than 80% parking events of the vehicles which belong to these market segments potentially lead to an exceedance of the evaporative emission limit in warm climate conditions up to a factor 4 (see small vehicle Figs. 6(a) and 7(a)).

Figs. 8 and 9 provide the total evaporative emissions for the small (a), medium (b) and large (c) size vehicle over different numbers of evaporative cycles for the province of Modena and Firenze (left scale), referring to an associated trip with a length between 7 and 8 km (average trips length, as derived from the activity data analysis, Section 3.1). The higher the number of evaporative cycles (i.e. the longer the parking duration), the higher the emissions. In this case the emissions set well above the threshold (bolded dashed line) from two evaporative cycles on, showing that, in general, the current evaporative emission control system could not be able to cope with parking period longer than one evaporative cycle. The evaporative emissions exceed the legislative limit for almost all the year, if the vehicle is parked for

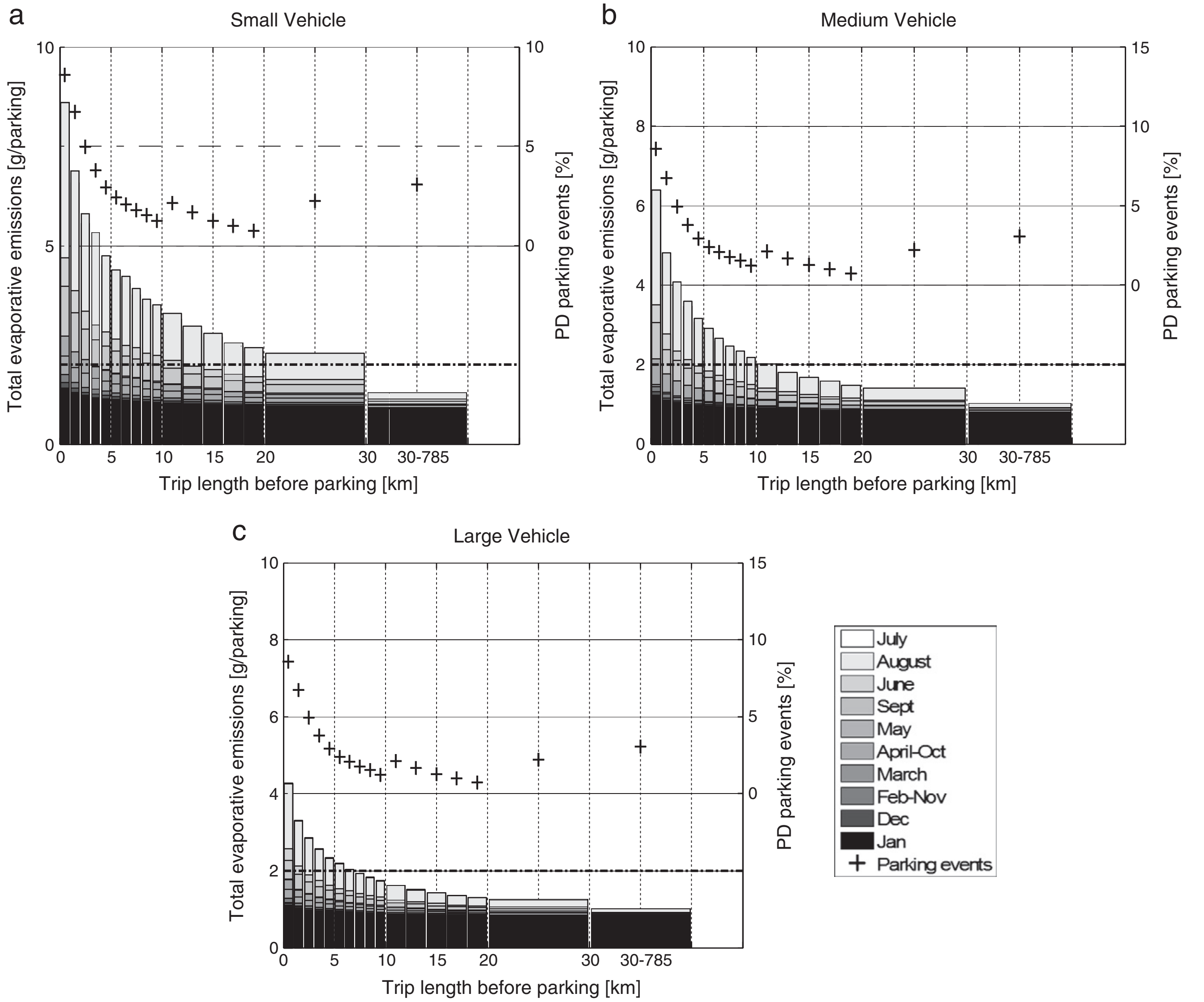

Fig. 7. Total evaporative emission distribution for the small (a), medium (b) and large size (c) over different trip lengths before a parking of one evaporative cycle (left scale). The bars report the absolute values, not cumulative quantities. PD of the parking events (right scale). Province of Firenze.

more than 4 evaporative cycles (i.e. see the fourth bar in Figs. 8 and 9). The larger the vehicles, the higher the evaporative emissions on long parking events (6–31 days), being the fuel tank bigger. The PD of the parking events is also reported (right scale, eighth row of Tables 3 and 4). Also in this case approximately half of the parking events last more than one evaporative cycle, being not represented by the evaporative emission regulation procedure. The results depicted in these figures also support the argument that, in spite of the fact that the evaporative emissions analysis is carried out only for 10% of the parking events (being the 90% marked as "0-cycle", as per Section 3.2), the weight on total evaporative emissions of this minority of events is non-negligible. In fact, even though the probability of very long events (i.e. from 6 evaporative cycle on) to occur is very low (i.e. below one event per vehicle, see Table 2), they are responsible of emissions two orders of magnitude higher that the legislation limit.

Fig. 10 shows the monthly averaged values of total evaporative emissions in grams per day, against the month and the vehicle size. These values refer to the fleet composition as reported in Section 3.4. The results show that the emissions per day are higher than the threshold (bolded dashed line) from June to September, regardless the vehicle size. Higher emissions are found for the small vehicle and in May emissions above the limit might occur for the small and medium-sized vehicles only. This is due to the ambient temperature, as given in Table 6, calling for a revision of the current evaporative emission regulation, either only during the summer months or along all the year.

Table 7 reports the results for the yearly averaged total evaporative emissions for the province of Modena and Firenze, depending on the vehicle size. In both provinces the averaged emissions for the small and medium vehicle are higher than the 2 g threshold, whilst they are below the threshold for the large vehicle. Of course total evaporative emissions can be lowered by re-designing the evaporative emission control systems, e.g. increasing the carbon canister volume or purging rate, or by optimising the purging strategy, as it already happens for the vehicles complying with the more restrictive US legislation (see Section 2.1). Therefore similar measures are likely to be taken into account also in Europe in case of a revision of the current evaporative type approval legislation. However the re-engineering aspects of the evaporative emission control systems to be applied are out of the scope of this paper.

5. Conclusions

The effectiveness of the European relevant legislation for evaporative emission control has been evaluated against real-world mobility

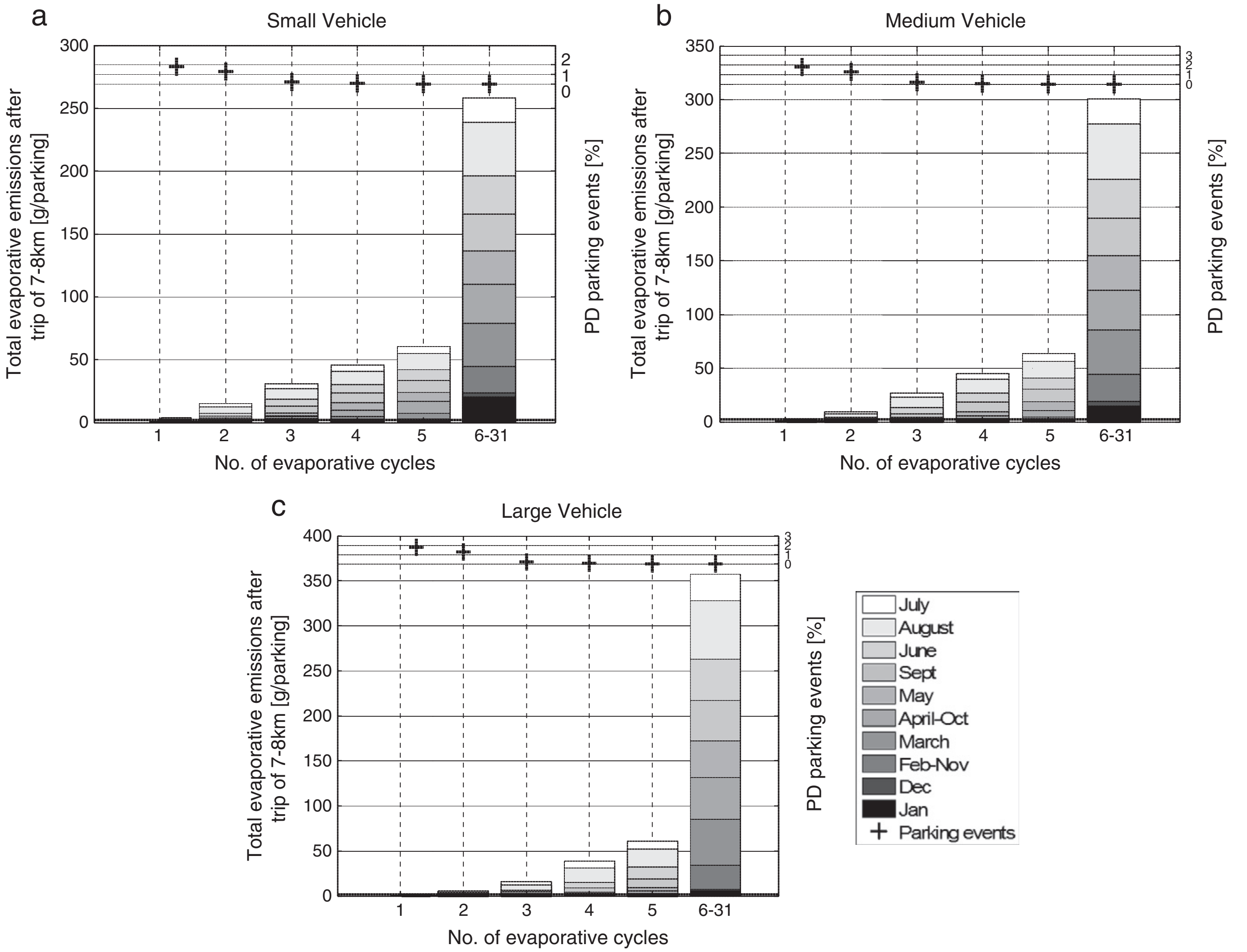

Fig. 8. Total evaporative emission distribution for the small (a), medium (b) and large size (c) over different evaporative cycles associated to a trip length between 7 and 8 km (left scale). The bars report the absolute values, not cumulative quantities. PD of the parking events (right scale) associated to these trips. Province of Modena.

data of two Italian provinces from activity databases by means of the emission simulation software COPERT. The objective of this analysis was to address to what extent the legislative type-approval test procedure covers the real-world driving/parking conditions.

The driving patterns used were collected on conventional fuel vehicles with GPS systems in two Italian provinces (i.e. Modena and Firenze) over a period of one month, accounting for approximately 28,000 vehicles and 36 million kilometres. These data were processed in order to derive the relation between the trip length and the parking duration as well as the rate of occurrence of parking events covering multiple evaporative cycles (i.e. 12-hour diurnal time windows considered relevant to the evaporative emissions).

These results were used as input for the a model, to calculate the evaporative emissions depending on real-world trip length and parking duration (i.e. carbon canister loading level), vehicle size and ambient temperature conditions. The mobility results show that the 33 km conditioning drive from the type-approval test procedure is representative of only 2.5% of real-world trips, and that the typical urban trip length sets well below it, often resulting in evaporative emissions above the type-approval limit of 2 g/test.

This is more prominent for small size vehicles (equipped with a smaller carbon canister than larger vehicles) and during the summer months. In particular considering one evaporative cycle, the results show that trips below 10 km for the small size, 4 km for the medium size and 2 km for the large size vehicle result in evaporative emissions above the threshold limit from June to August, and that more than 80% of the considered parking events potentially exceed the limit in warm climate conditions up to a factor 4. In addition, by considering the average trip length in urban driving, the emission limit is exceeded all over the year if the vehicle is parked for more than 4 days, potentially increasing, in the worst case, to a value of two orders of magnitude larger than the limit.

These results suggest that the current type-approval test procedure for evaporative emissions does not effectively cover real-world driving and parking conditions. In the long term, a worldwide harmonised test procedure for evaporative emissions is foreseen and it should be developed within UN-ECE GRPE (Working Party on Pollution and Energy), working group for WLTP (Worldwide Harmonised Test Procedure for Light Duty Vehicles). However, a revision of the European procedure is considered necessary also in the short term, since the actual passenger car will be on the roads for many years and a future worldwide harmonised procedure will result in significant benefits only after some years from its introduction, depending on the car fleet renewal rate.

Future developments will be targeted to extend this work to different European geographical areas and periods of the year, better addressing the seasonal variation of the evaporative emissions, their geo-referenced distribution over the territory, to suggest the most effective measures to be considered for their control and reduction in real-world conditions.

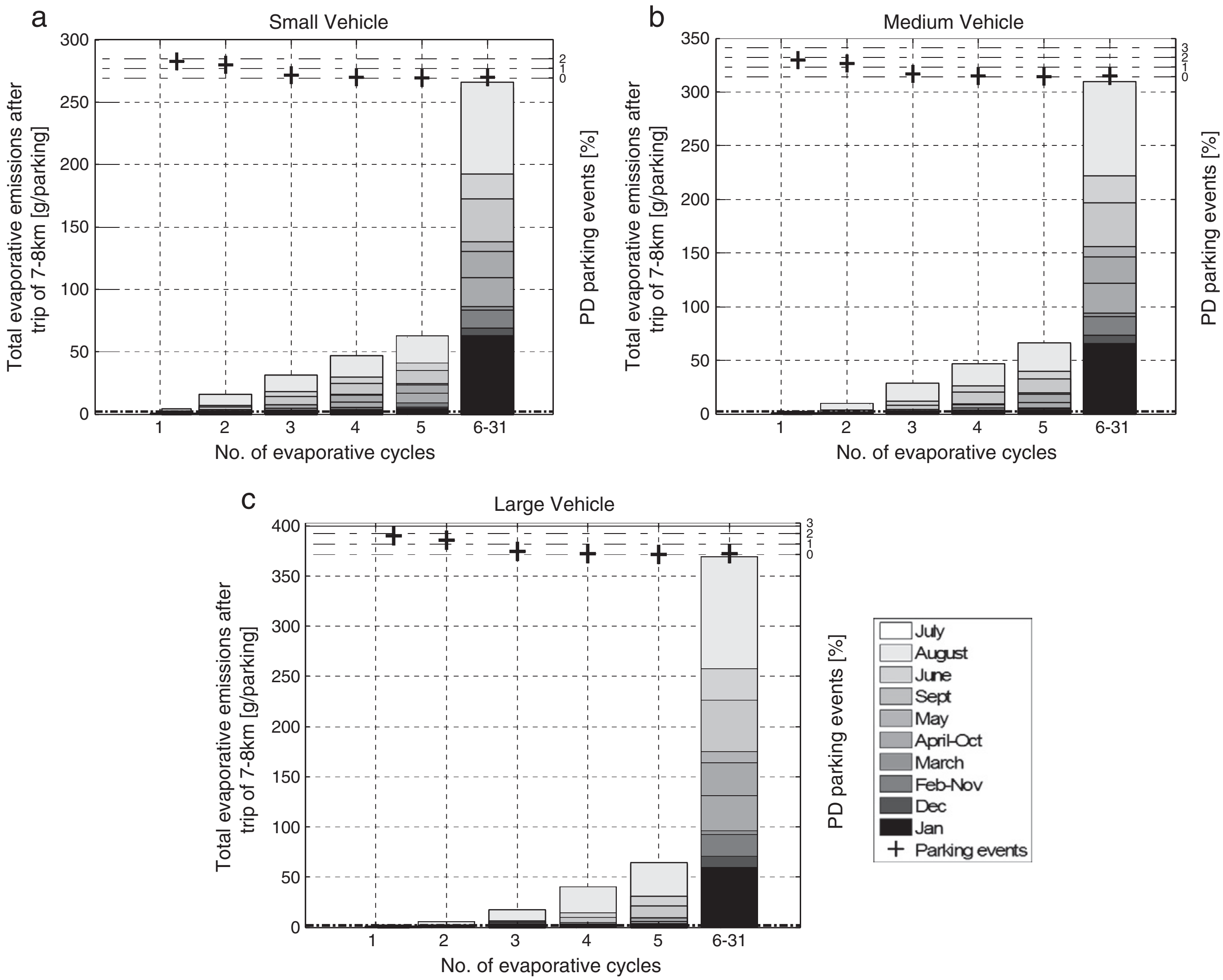

Fig. 9. Total evaporative emission distribution for the small (a), medium (b) and large size (c) over different evaporative cycles associated to a trip length between 7 and 8 km (left scale). The bars report the absolute values, not cumulative quantities. PD of the parking events (right scale) associated to these trips. Province of Firenze.

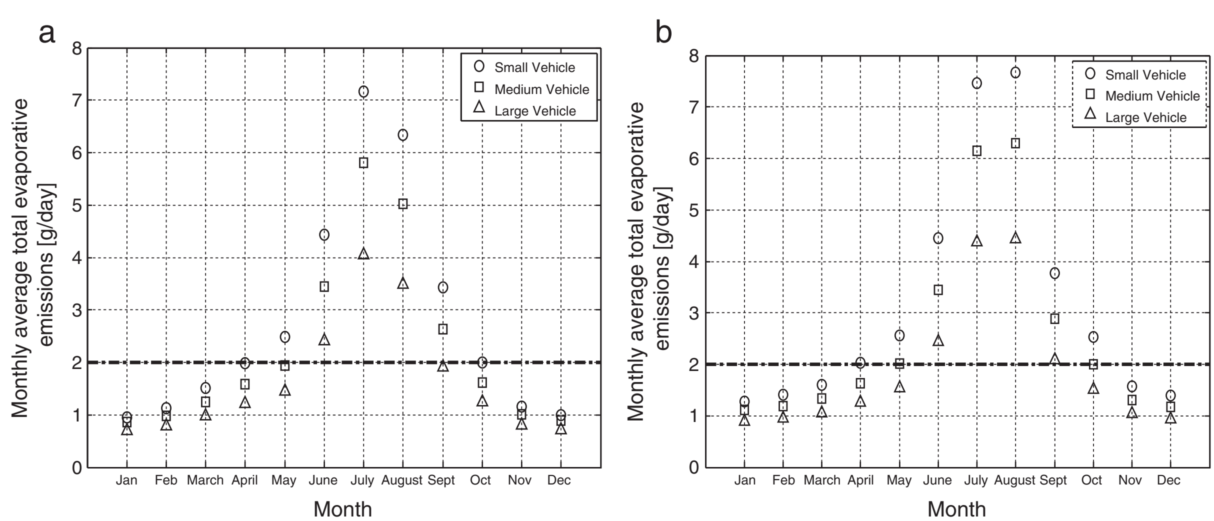

Fig. 10. Monthly average total evaporative emissions (grams/day). Province of Modena (a), province of Firenze (b).

Table 7
Yearly average total evaporative emissions in grams per day for the province of Modena and Firenze.

Vehicle size	Modena province	Firenze province
Small	2.799	3.145
Medium	2.256	2.547
Large	1.650	1.878

Conflict of interest

There are no actual or potential conflicts of interest including any financial, personal or other relationships with other people or organizations related to the publication of the current manuscript. This holds for three years from the submission date.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2014.04.053.

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