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European-wide study on big data for supporting road transport policy

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A B S T R A C T

This paper presents the latest achievements of TEMA (Transport Technology and Mobility Assessment) platform, designed to harness the potential of big data to support road transport policies in Europe. The platform relies on datasets of real world driving and mobility patterns collected by means of navigation systems and it is developed by the EC Joint Research Centre since 2012. Previous studies have demonstrated the potential of the platform in assessing real world emissions from conventional fuel vehicles and exploring the impact of the deployment of electrified vehicles in terms of usability, technology potential, energy requirements and infrastructural design. These last studies have been carried out on two pilot regions, i.e. the Italian provinces of Modena and Florence, whilst this article presents the earliest results achieved enlarging the study to a European-wide scale. To this purpose, results from additional fourteen new regions are presented, i.e. Amsterdam (NL), Brussels (BE), Luxembourg (LU), Paris (FR), Lisbon (PT), Krefeld (DE), Warsaw (PL), Bratislava (SK), Vienna (AT), Ljubljana (SI), Zagreb (HR), Budapest (HU), Sofia (BG), Athens (GR). The complete dataset accounts for approximately 2.57 billion records, 139 million driven kilometres and 632,186 monitored vehicles, being one among the most extensive driving datasets ever processed for policy support studies. This work constitutes the first attempt for initiating a continental scale study of driving behaviour in Europe, with the aim of showing how the proposed approach allows for unprecedented opportunities to shape the future of road transport.

Keywords:
Big data and data mining
Transport policy
Urban mobility
GPS
Urban environment

1. Introduction

In Europe over 70% of citizens live in urban areas (Eurostat, 2011) and projections forecast an increase to nearly 80% by 2030, (United Nations Population Fund, 2007), (European Environment Agency (EEA), 2006). Densely populated cities increase strains on energy, transportation, resources, housing and public spaces needs, and, despite the efforts made so far, there are still many challenges, particularly concerning lowering Greenhouse Gases (GHGs) and pollutants emissions. Road transport contributes to about one–fifth of the total carbon dioxide emissions in Europe, representing the sector with the second highest emissions, just behind the energy sector, and grown by nearly 23% between 1990 and 2010 (European Commission Website, 2014). This calls for major changes for future mobility, as outlined by EC White Paper 2011 (European Commission, 2011), by the Strategy and Action Plan for creating an Energy Union (European Commission, 2015) and by the European strategy for low-emission mobility (European Commission, 2016).

The development of a sustainable mobility implies moving towards a transport system which turns to be a combination of intelligence, low carbon energy sources and adaptable services (Hautala et al., 2014), with integrated networks of two or more modes of transport which interplay seamlessly. Such integration must optimise the transport services, and, at the same time, improve safety, reduce the energy consumption and systems' overall environmental impact (European Parliament, 2017). Transport demand will certainly increase in the EU of the next decade, pulled by five main drivers, (European Parliament, 2016):

- population growth and intra-border immigration that will increase the mobility demand within the EU;
- increasing urbanization that will place significant pressure on major cities and particularly on capital regions. In the last 15 years some countries have seen population growth of over 25% whilst others have lost almost 20%, with a tendency to move towards Western Europe;
- evolution of the employment market that will demand for increased flexibility and hence flexible travel demand;
- income growth that should accompany increased employment and gross domestic product (GDP) growth and that will act as a continuing upward pressure on mobility in most areas;
- mobile technologies and internet with the potential of such

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Nomenclature

BEV	battery electric vehicle
DaaS	delivery as a service
EU	European Union
EV	electric vehicle
GDP	gross domestic product
GIS	geographic information systems
GHG	greenhouse gas
GPS	global positioning system
HDV	heavy duty vehicle
HEV	hybrid electric vehicle
HVAC	heating, venting and air conditioning
ICT	information and communication technology
IoT	internet of things
LDV	light duty vehicle
MaaS	mobility as a service
MDV	medium duty vehicle
PHEV	plug-in hybrid electric vehicles
TEMA	transport technology and mobility assessment
UF	utility factor
V2G	vehicle-to-grid

technologies to substitute physical mobility with virtual mobility, even though there is no evidence of the reduction of the traveling today; for example the rise of e-commerce seems to be creating a significant pressure for light commercial vehicle traffic.

All these factors drive towards the new concept of Mobility as a Service (MaaS) and Delivery as a Service (DaaS) with a mind shift from the idea of owning a vehicle to the idea of purchasing mobility as a service through a digital interface, leaving the system deciding about the most effective and efficient solution to fulfil the journey.

In this framework Information and Communication Technology (ICT) will play a major role, becoming a functional element of the energy and transport infrastructure, enabling a completely new level of optimization and automation (Hautala et al., 2014). In fact, the last decade has been characterised by the introduction of a number of ICT-driven innovations which in various ways contribute to better use the capacity of the systems and provide better information to users. These include smart intersection control in urban areas, ramp metering on access to motorways, contactless toll payment systems, parking guidance systems and variable message signs that display information associated with congestion, alternative routes and many others (European Parliament, 2016). They make large use of sensing combined with Global Positioning System (GPS) technology to deliver real time information to travellers, through an interface that is, in most cases, the mobile phone. Smartphones are, in fact, increasing their stakes as primary communication device and in Western Europe they are used in everyday life by approximately half of the population. This is accompanied by vertical rate of growth of mobile data traffic, and it is estimated that the average mobile user consumed in 2013 as much as 39 times more data than in 2009 (Lee et al., 2013).

The potential of smartphones in relation to transport application is depicted by Mokhtarian (1990) which identifies four relationships between traveller and digital device:

- substitution, where devices decrease travel;
- enhancement, where technology changes the utility of particular modes of travelling, affecting choice between modes;
- efficiency, where telecommunications make travel more efficient;
- indirect, where telecommunications affect land use, which in turn affect travelling.

The rise of the company Uber provides a clear demonstration of how mobile technology can quickly reconfigure existing aspects of mobility in new ways (European Parliament, 2016).

Also the car itself is nowadays undergoing a data revolution. Modern vehicles are equipped with about 40 microprocessors and

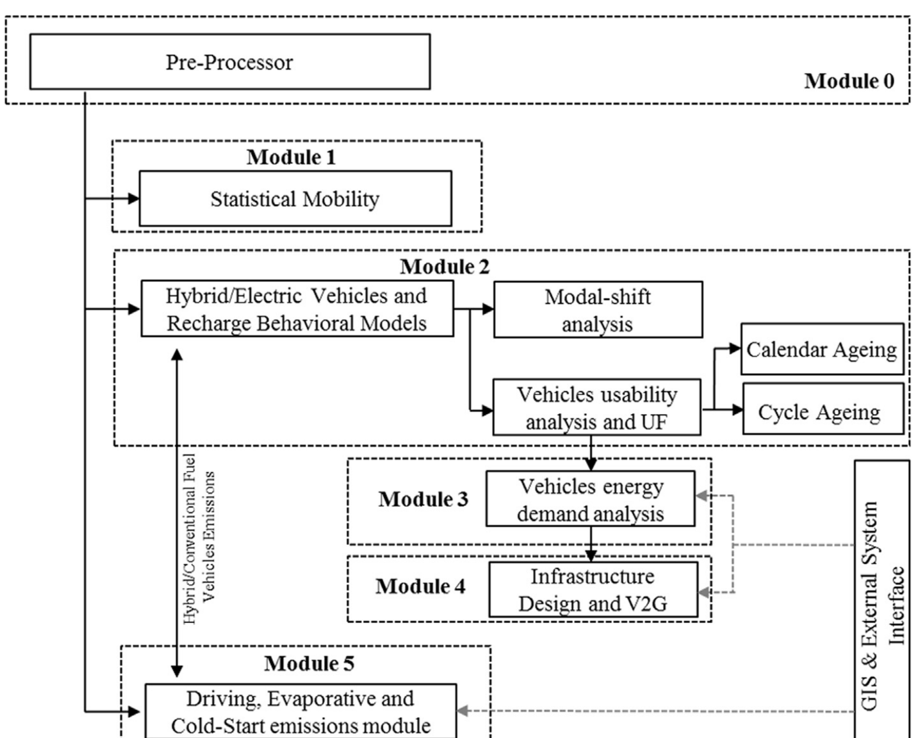


Fig. 1. Structure of TEMA platform.

Table 1
Data overview and shares between private and commercial vehicles.

		No. of days [#]	No. of vehicles [#]	Records [1 0 ^{6}]	Trips [1 0 ^{6}]	Total trips lengths [km·10^6]	No. of trip per day(mean) [#]	Trip length [km](mean)	Daily driven distance (mean) [km]	Private vehicles share	Commercial vehicles share	Analysed sample (% of registered vehicles in the province area)
Private Vehicles	Province of Modena	31	16,263	16.00	1.9	14.98	6.6	7.8	51.9	91.6%	8.4%	3.68%
	Province of Florence	31	12,478	32.01	2.6	20.66	6.4	8.0	51.3	90.9%	9.1%	1.82%
	Province of Amsterdam	7	197,756	466.28	1.1	19.86	1.9	19.7	37.2	83.2%	16.8%	17.17%
	Province of Brussels	14	96,802	277.05	1.1	11.21	7.9	7.7	55.2	91.2%	8.8%	16.26%
	Province of Paris	7	171,220	963.27	2.3	38.39	4.2	17.0	71.7	99.1%	0.9%	2.43%
	Province of Luxembourg	7	14,090	24.33	0.08	1.0	2.5	11.9	30.1	92.0%	8.0%	17.63%
Commercial Vehicles	Province of Lisbon	7	7,522	66.16	0.16	2.48	5.8	15.0	86.1	–	100%	0.47%
	Province of Krefeld	7	4,160	22.11	0.01	0.97	1.7	88.8	151.7	2.9%	97.1%	3.12%
	Province of Warsaw	7	862	3.79	0.003	0.16	2.4	51.8	124.3	2.3%	97.7%	0.08%
	Province of Bratislava	7	18,296	23.08	0.04	1.0	1.5	22.9	35.0	–	100%	9.65%
	Province of Vienna	7	9,943	49.44	0.06	2.14	13.8	37.9	134.2	0.9%	99.1%	0.87%
	Province of Ljubljana	7	11,616	95.77	0.08	4.04	3.4	45.3	148.6	0.7%	99.3%	7.05%
	Province of Zagreb	7	12,036	91.66	0.15	3.79	4.6	24.3	104.6	14.0%	86.0%	3.87%
	Province of Budapest	7	32,410	320.45	0.32	14.10	4.1	44.1	179.0	0.1%	99.9%	4.89%
	Province of Sofia	7	11,368	79.60	0.20	3.28	5.4	16.4	87.4	–	100%	1.78%
	Province of Athens	7	15,366	42.09	0.13	1.49	4.9	11.0	53.9	–	100%	0.71%
	TOTAL		632,186	$2.57 \cdot 10^3$	10.19	139.57						
	TOTAL (private vehicles)		506,105	$1.77 \cdot 10^3$	8.56	101.87						
	TOTAL (commercial vehicles)		126,081	$0.80 \cdot 10^3$	1.63	37.70						

Table 2
Comparison of mobility for Europe and the USA.

Source	Year	Country	Average no. of trips per day [#]	Average distance per trip [km]	Poll size (effective)		Comment
					households [$\cdot 10^3$]	persons[$\cdot 10^3$]	
Marconi et al. (2004)	2004	Switzerland	4.0	10.4	28	29	CATI geo-coding system surveys
		Germany	3.9	11.1	50	130	
		USA	4.1	17.9	66	–	
		Norway	3.6	11.9	–	20 (1 year)	Written surveys
		The Netherlands	3.1	–	64.2	146.5	
		Austria	3.0	9.5	12.8	–	
		Great Britain	2.8	11.3	10	23	
		France	3.2	2.9	14.2	3 (years)	Face-to-face and written surveys
Eurostat: Passenger mobility in Europe (EUROSTAT, 1999–2001)	1999–2001	Switzerland	3.6	13	Data collected between1999 and 2001; data collected based on populations of up to 40,000 households depending on the studied country		
		Germany	3.4	11.7			
		France	2.9	12.2			
		Latvia	1.9	4.6			
		The Netherlands	3.3	10.2			
		Austria	3	9.4			
		Finland	2.9	15.4			
		Sweden	2.7	16.3			
		United Kingdom	2.9	11			
		Denmark	2.7	12.7			
		Norway	3.3	11.5			
ISFORT (Mobility in Italian cities) (ISFORT, 2008)	2008	Italy	3.12	12	Average of mobility in big cities 15,000 interviews per year, age between 14 and 80, working days		
ISFORT (2015)	2015	Italy	2.7	11.5	Average of mobility in big cities 15,000 interviews per year, age between 14 and 80, working days		
ACI CENSIS (2012)	2012	Italy	3 on week days, 2.1 on weekends	10 on week days 11 on weekends	Average of various cities		
GPS data from Table 1	2011	Prov. Modena	6.6	7.8	GPS		
	2011	Prov. Florence	6.4	8.0			
	2015	Prov. Amsterdam	1.9	19.7			
	2015	Prov. Brussels	7.9	7.7			
	2015	Prov. Paris	4.2	17.0			
	2016	Prov. Luxemburg	2.5	11.9			
	2015	Prov. Lisbon	5.8	15.0			
	2015	Prov. Krefeld	1.7	88.8			
	2016	Prov. Warsaw	2.4	51.8			
	2016	Prov. Bratislava	1.5	22.9			
	2016	Prov. Wien	13.8	37.9			
	2016	Prov. Ljubljana	3.4	45.3			
	2016	Prov. Zagreb	4.6	24.3			
	2016	Prov. Budapest	4.1	44.1			
	2016	Prov. Sofia	5.4	16.4			
	2015	Prov. Athens	4.9	11.0			

dozens of sensors that collect data which are processed in real-time to maximise the performance, efficiency, and safety of the vehicle (Hitachi, (2015)). According to Siegel (2016) today's modern car generates twenty-five gigabytes of data every hour and, of that data, about 1–2 kilobytes are only stored and fully utilised. Twenty-five gigabytes is also the amount of data that the future connected car will upload to the cloud every hour, generating immense business opportunities. According to McKinsey&Company (2016), the expected growth of the value pool from car data and shared mobility could add up to more than USD 1.5 trillion by 2030, and the foreseeable proliferation of new features and services will turn car data into a key topic on the agenda of the auto industry. New players are entering this competitive area, as these companies are familiar with collecting enormous amounts of data, processing them, combining them with different sources, and deploying features and services that customers are willing to pay for. The Internet of Things (IoT) will increasingly explore the possible applications of all this data that has been hidden until today or considered too dense to be analysed (i.e. traffic patterns, driver behaviour, failure prediction) (Siegel, 2016).

In this context, big data has the potential of revolutionising the way in which transport policies are conceived driving the process of re-definition of the current transport policies towards more effective implementation of the actions that need to be undertaken to meet the long-term goals of the Union. Recent studies prove the potential of data, being used to measure commuting efficiency in megalopolis (Zhou et al., 2014), to explore public transport users' behaviours (Tao et al., 2014), to simulate individual mobility choices in carpooling (Galland et al., 2014) and to classify activity patterns (Liu et al., 2015), (Hasan and Ukkusuri, 2014), with applications in the fields of mobility networks design and infrastructures (Marcianó et al., 2015), (Xu et al., 2013), (Ortega et al., 2014) and multi-modal transportation systems (Zhang et al., 2013). On one hand these studies constitute interesting

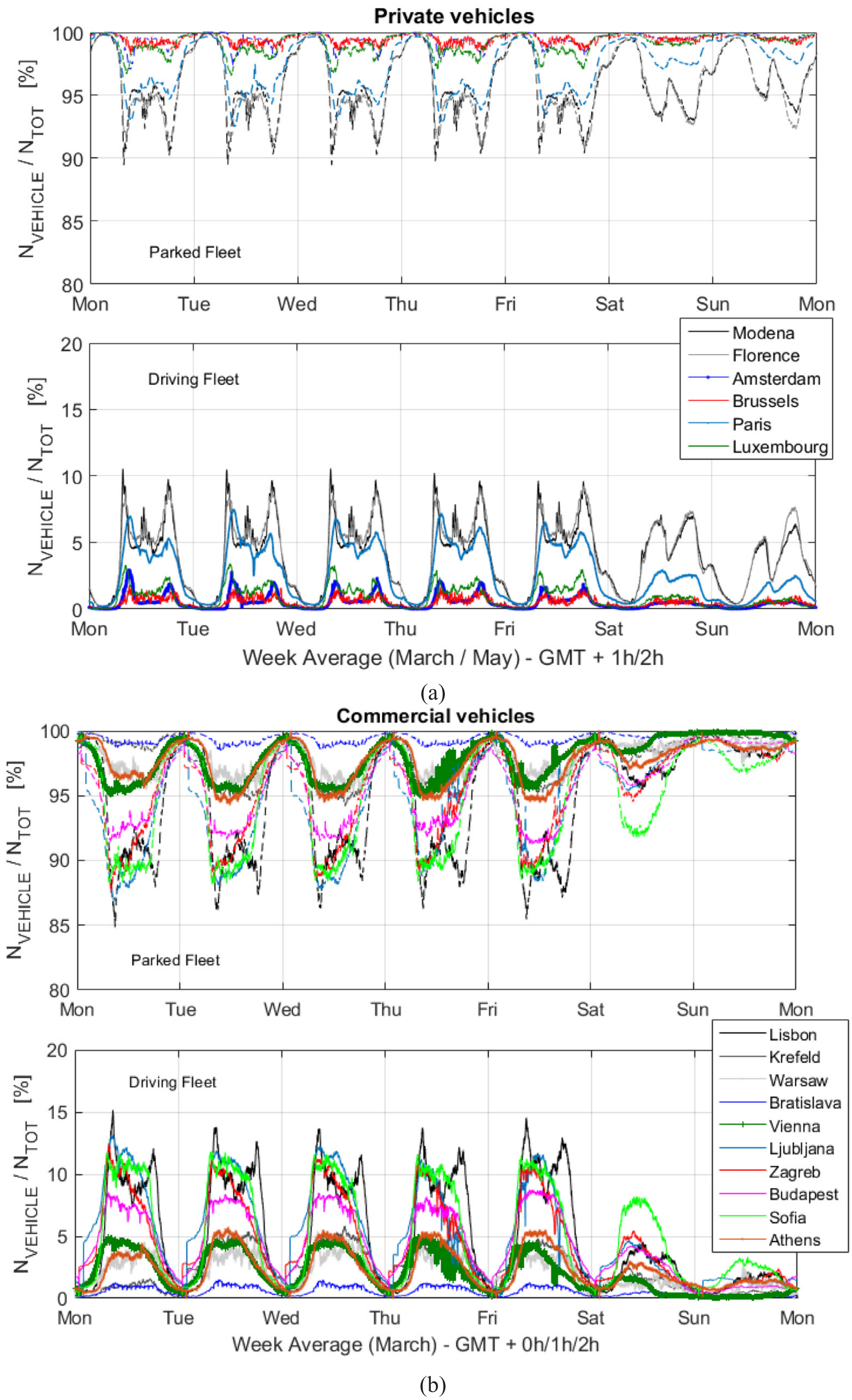


Fig. 2. Share of the private (a) and commercial (b) vehicles in motion and parked in time.

Table 3
Fleet shares per intervals of daily travelled distances.

	Private vehicles[%]						Commercial vehicles[%]					
	≤30 km	≤50 km	≤100 km	≥150 km	≥500 km	≥1,000 km	≤30 km	≤50 km	≤100 km	≥150 km	≥500 km	≥1000 km
Province of Modena	45.7	66.8	89.5	4.7	0.14	0.003	35.7	53.4	78.2	12.2	0.67	0.012
Province of Florence	49	68.3	88.6	5.3	0.18	0.003	36.3	53.6	77.9	11.7	0.57	0.008
Province of Amsterdam	57.9	74.1	92.3	2.4	0.0007	0	36	50.9	73.5	15.2	0.25	0.028
Province of Brussels	53.8	66.1	82.0	9.7	0.17	0.016	7.6	13.3	31.1	53.6	18.7	4.4
Province of Paris	35.7	52.2	76.6	12.1	0.20	0.0002	12.7	20.6	40.5	43.9	2.55	0
Province of Luxembourg	62.0	84.5	97.8	0.38	0	0	38.8	78.9	95.2	0.87	0	0
Province of Lisbon	0	0	0	0	0	0	20.8	37.2	69.3	14.6	0.15	0.035
Province of Krefeld	43.8	57.6	80.5	11.0	0	0	12.0	22.2	43.0	40.5	2.4	0.034
Province of Warsaw	33.3	46.7	60.0	30.0	0	0	39.2	47.3	59.1	33.9	2.3	0
Province of Bratislava	0	0	0	0	0	0	64.2	72.2	94.8	2.6	0.014	0
Province of Vienna	2.3	6.7	23.6	66.3	1.1	0	25.1	34.6	52.7	36.5	1.2	0.013
Province of Ljubljana	10.5	21	42.6	33.3	0	0	8.9	16	36.8	41.8	0.5	0.061
Province of Zagreb	25.4	40.8	66.8	20.2	0.56	0.26	19.7	32.9	59.5	24.2	0.38	0.042
Province of Budapest	12.5	25	45.8	31.3	2.1	0	9.7	16.5	33.2	52.4	2.0	0.051
Province of Sofia	0	0	0	0	0	0	29.6	46.6	71.9	17.4	0.57	0.060
Province of Athens	0	0	0	0	0	0	46.0	61.7	85.2	6.5	0.13	0.025

advances of big data in transport, but, on the other hand, they are limited to single case studies and applications, mostly grounded on data averaging and data aggregation approaches.

This article presents the follow up of a series of articles from the authors, summarized in (De Gennaro et al., 2016a) that explored several aspects of big data for transport, based on pilot driving datasets from the Italian provinces of Modena and Florence. These studies present the application of the EC TEMA (Transport Technology and Mobility Assessment) platform, developed by the JRC since 2012, in respect to quantifying real world emissions from conventional fuel vehicles and exploring the effect of the deployment of electrified vehicles in terms of usability, technology potential, energy requirements and infrastructural design. In this work the mobility study is enlarged to a EU-wide scale, including additional fourteen datasets from Amsterdam (NL), Brussels (BE), Luxembourg (LU), Paris (FR), Lisbon (PT), Krefeld (DE), Warsaw (PL), Bratislava (SK), Vienna (AT), Ljubljana (SI), Zagreb (HR), Budapest (HU), Sofia (BG), and Athens (GR). The data consists of 632,186 monitored vehicles in total, equivalent to 10.2 million trips and parking events and 139.6 million kilometres. The databases have been collected by private companies (Octo Telematics Italia S.r.l., 2013), (Be-Mobile, Traffic and Mobility, 2016), (Universalis, 2016), and processed by the EU Commission Joint Research Centre. This work focuses on few applications of TEMA modules, related to the statistical mobility analysis at European scale and geographic mapping of some results to depict the extensiveness of the datasets and the challenge overcome to process and handle this large set of data. This constitutes a first attempt for a continental scale pilot study of travel behaviour in Europe, with the aim of showing how the presented data and processing methodologies allows for unprecedented opportunities to shape the next generation transport policies towards a zero emission society.

2. Background information and methodology

2.1. Introducing TEMA

TEMA is a data processing platform natively interfaced with GNNS, developed for supporting the development of transport policies in Europe (De Gennaro et al., 2016a), (European Commission, Joint Research Centre, 2012). It makes an extensive use of data mining, and it has been developed according to different policy requests in a modular approach, resulting in a flexible software environment capable of testing the effects of introducing new vehicle technology in real-world mobility on a regional scale. The platform at moment includes five main modules beyond the pre-processor (i.e. Module 0) according to the structure reported in Fig. 1.

The applications of TEMA carried out so far included:

- quantification of the real-world potential of deploying electrified vehicles under different technological and infrastructural constraints, (De Gennaro et al., 2014a), (Paffumi et al., 2015);
- quantification and geo-referencing of the shift from oil to electric energy and the impact on the electricity distribution grid of EVs (De Gennaro et al., 2014b);
- design of a customer-driven smart recharge infrastructure and tailored V2G application in public areas (De Gennaro et al., 2015), (Paffumi et al., 2016);
- evaluation of the driving and evaporative real world emissions from the current fleet of conventional vehicles and gaseous emissions reduction potential from the introduction of new vehicle technologies (Martini et al., 2014), (De Gennaro et al., 2016b);
- evaluation of the Utility Factor (UF), based on collected vehicle activity data to evaluate the real world conditions of use of plug-in hybrid electric vehicles, (Paffumi et al., (2018));
- support to the eco-innovation technologies assessments, (Lodi et al., 2018);
- in-vehicle battery durability assessment (De Gennaro et al., n.d.), (Loiselle-Lapointe et al., 2018).

2.2. Introducing the data

As per section above, TEMA is a data processing platform that relies on real-world mobility input data. In respect to the previous applications, in this work the platform is analysing an extensive input dataset. It consists of sixteen databases of navigation data collected by GPS (Octo Telematics Italia S.r.l., 2013), (Be-Mobile, Traffic and Mobility, n.d.), (Universalis, n.d.), in fifteen European countries, as summarised in Table 1. The data includes 632,186 monitored vehicles equivalent to 2.57 billion GPS records and 10.19 million trips and parking events, for a cumulative driving distance of 139.57 million kilometres.

The data acquisition campaign related to the Italian provinces of Modena and Florence (Octo Telematics Italia S.r.l., 2013) extended over a period of one month (May 2011) and has originally involved 52,834 conventional fuel vehicles in Modena and 40,459 vehicles in Florence (i.e. respectively 12.0% and 5.9% of the fleet in these provinces) (De Gennaro et al., 2014a). The analysis is then restricted to 16,263 vehicles in Modena (30.7% of the original sample) and 12,478 vehicles in Florence (30.8% of the original sample), in order to consider only the share of the fleet predominantly driven in urban areas (defined as more than 50% of the trips carried out within the province area). The

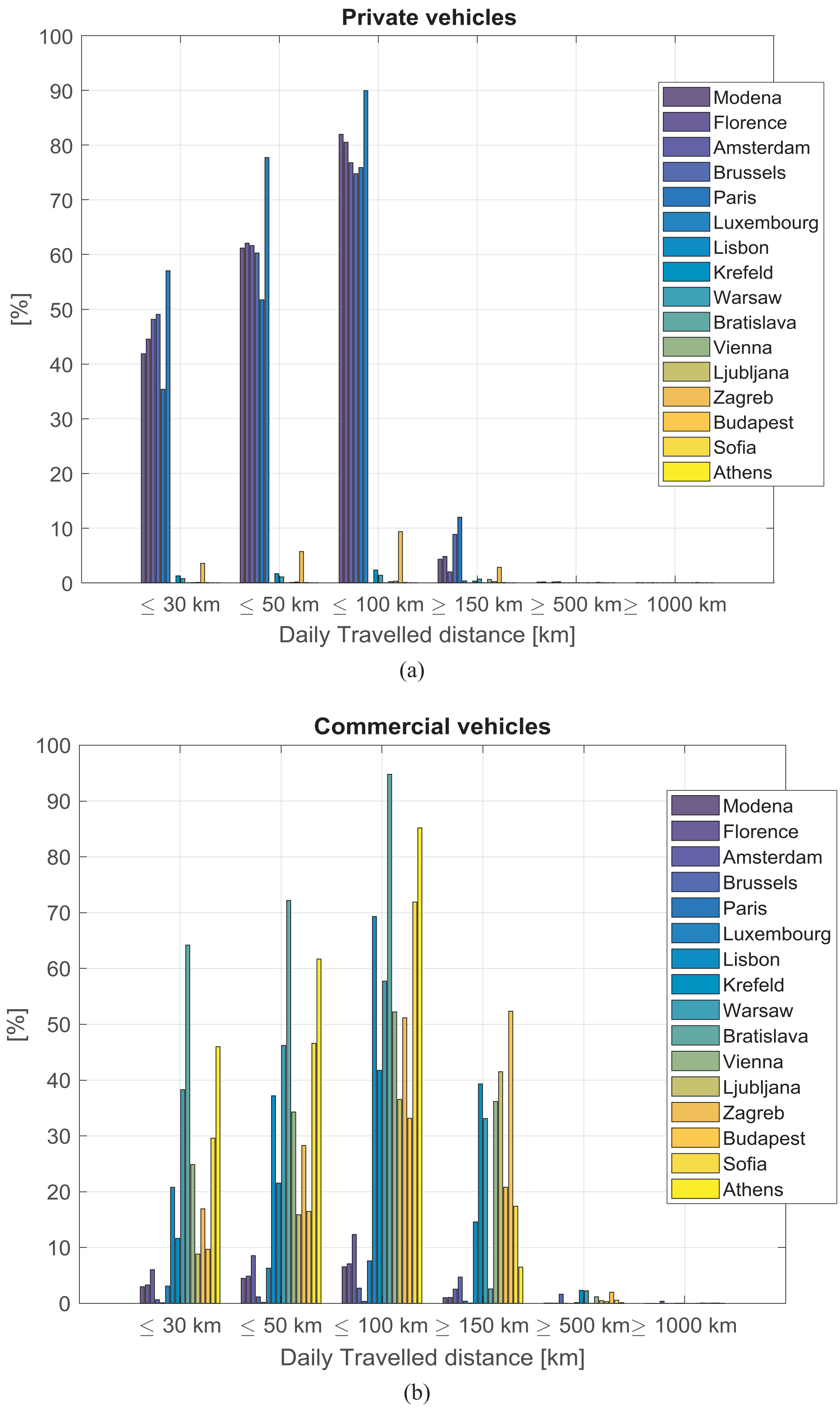


Fig. 3. Daily travelled distance for the private (a) and commercial (b) vehicles.

analysed databases consist of approximately 16.9 million records (representative of 14.98 million km and 2.64 million trips) and 33.4 million records (representative of 20.66 million km and 1.87 million trips) respectively. In both provinces about the 91% of the vehicles were registered to the name of a physical person while the remaining share were vehicles registered to the name of a commercial activity. To the purpose of the driving behaviour statistical analysis these two groups of vehicles have been treated separately; the first has been referred as private vehicles (mainly Light Duty Vehicles (LDVs)), while the second as commercial vehicles (light vans, Medium Duty Vehicles

Table 4
Average trip distance, trip duration, parking duration and trip speed for all the databases.

		Average trip distance [km]	Average trip duration [m]	Average parking duration [h]	Average trip speed [km/h]
Private vehicles	Province of Modena	7.69	11.63	4.07	28.92
	Province of Florence	7.85	13.0	4.33	26.13
	Province of Amsterdam	19.68	14.32	1.14	78.75
	Province of Brussels	7.75	9.13	1.45	51.98
	Province of Paris	16.97	20.05	1.18	44.87
	Province of Luxembourg	11.88	13.99	1.703	54.491
Commercial vehicles	Province of Lisbon	14.96	22.44	1.07	35.574
	Province of Krefeld	90.51	90.84	0.80	65.09
	Province of Warsaw	51.84	55.90	0.94	45.41
	Province of Bratislava	22.93	22.89	0.40	50.17
	Province of Vienna	37.43	35.96	0.48	57.87
	Province of Ljubljana	50.69	75.79	0.87	44.15
	Province of Zagreb	29.31	45.63	0.99	36.56
	Province of Budapest	44.14	43.25	0.91	49.28
	Province of Sofia	16.37	23.40	0.94	27.33
	Province of Athens	11.0	26.15	0.69	25.19

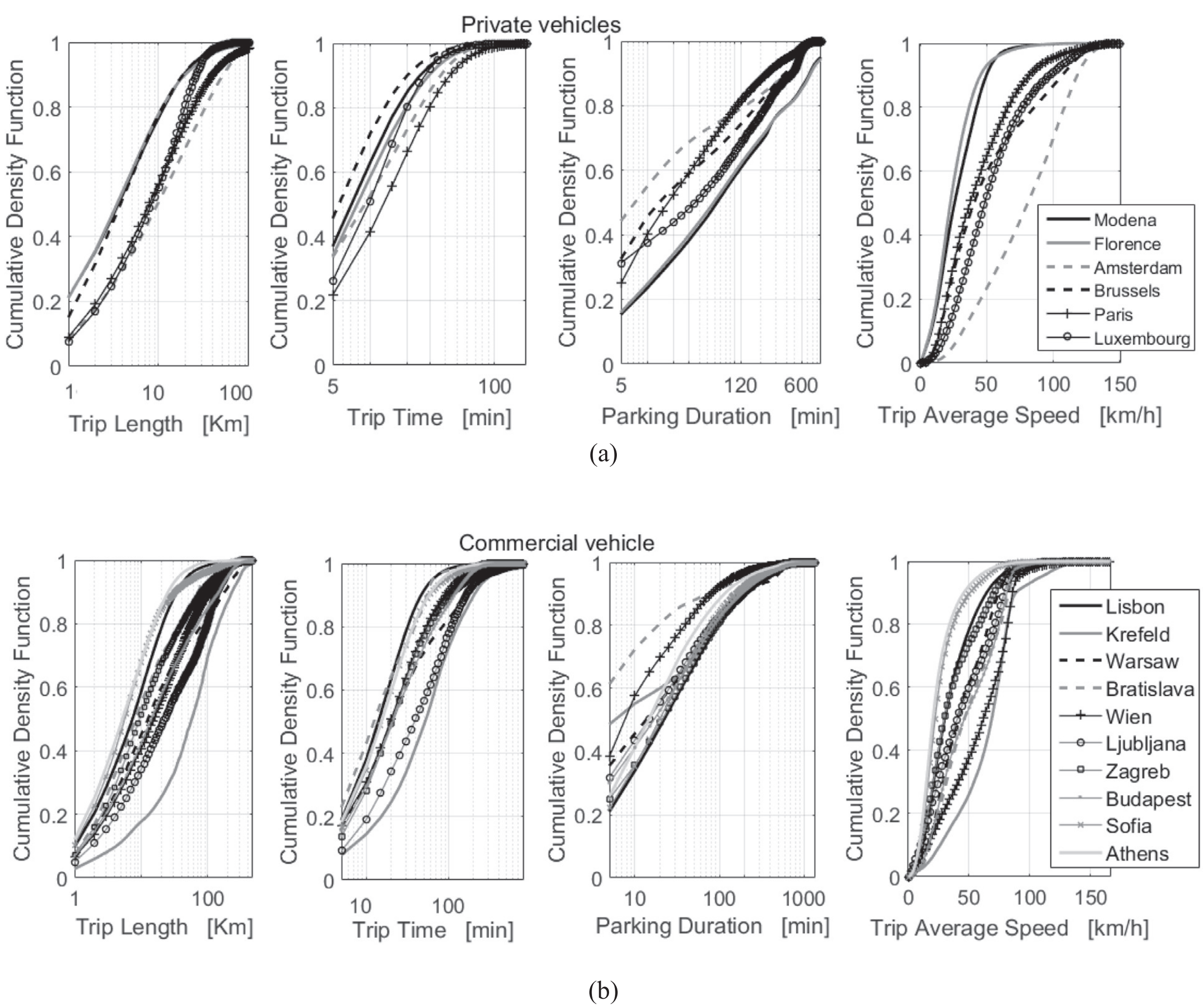


Fig. 4. Cumulative distribution functions of the averaged trip length, trip time, trip speed and parking duration; (a) private vehicles and (b) commercial vehicles.

(MDVs) and Heavy Duty Vehicles (HDVs)).

The data referring to all the other provinces (Table 1) has been purchased from the private companies Be-Mobile, Traffic and Mobility (n.d.) and Universalis (n.d.). These databases refer to an analysis period of one week (2–8 March 2015, for Amsterdam, Lisbon, Krefeld and Athens, 9–15 March 2015 for Paris and 7–13 March 2016 for Luxembourg, Warsaw, Bratislava, Vienna, Ljubljana, Zagreb, Budapest and Sofia) except the case of Brussels for which two weeks monitoring are available (2–15 March 2015). The vehicles are monitored up to the boundary of the countries, when a label indicating “leaving/entering the monitoring area” is added to the vehicle records. Information on the road classification, such as, highways, national roads or urban roads and road speed limits, where available, are also provided in the vehicle databases together with an extra label indicating the GPS system of the

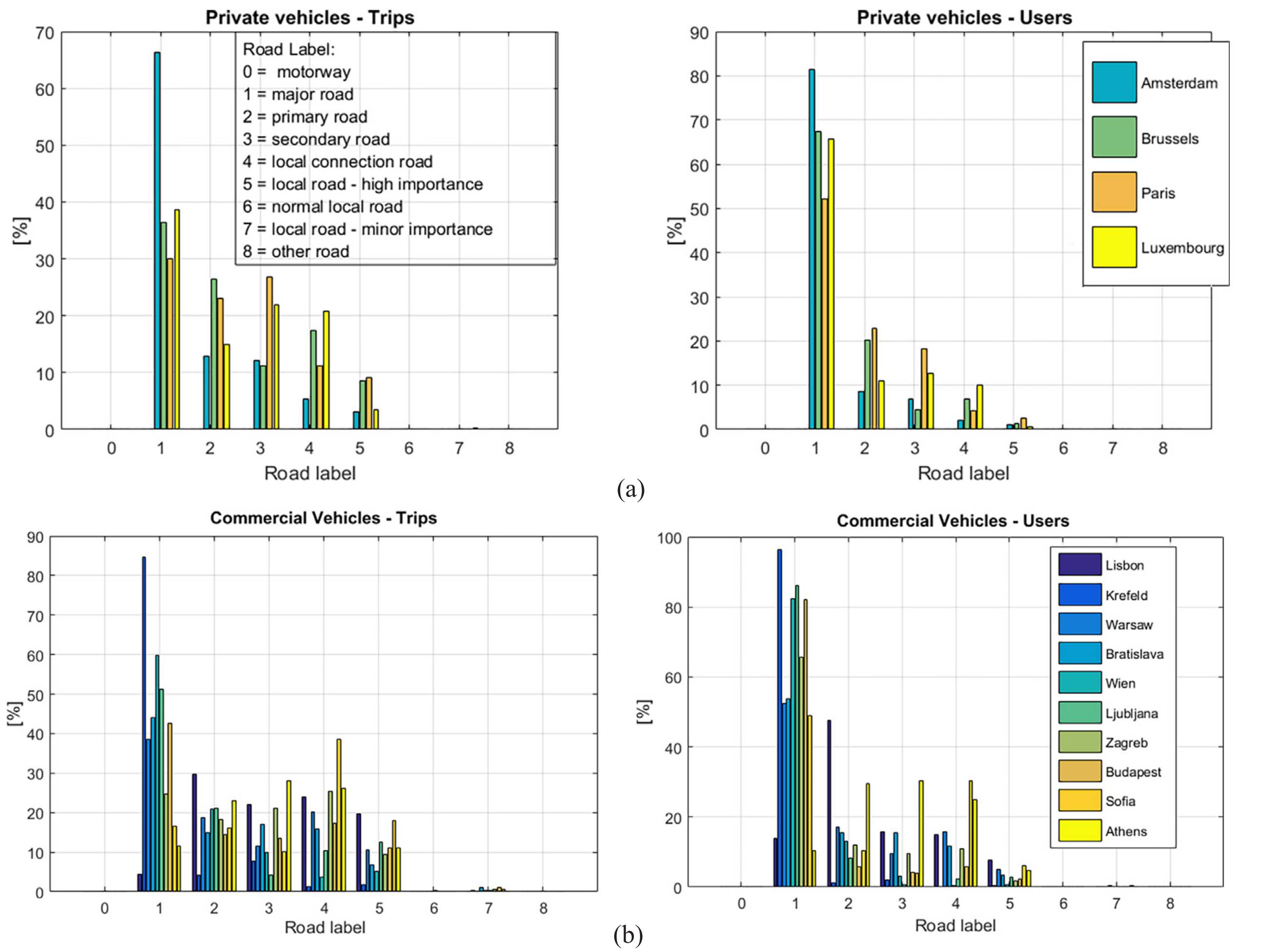


Fig. 5. Road type share for all the trips (left side) and users (right side) for private vehicles (a) and commercial vehicles (b). Data are not reported for Modena and Florence because unavailable.

vehicle that generated the data: (1) built-in fleet management system (mostly installed on HDVs, thus referred to as commercial vehicles), (2) telematics and navigation systems (mostly installed on LDVs, thus referred to as private vehicle) and (3) smartphone applications (mostly used in LDVs, thus referred to as private vehicles also). The categorisation in private and commercial vehicles is followed through the full paper and their share is consistently reported in Table 1. The data was acquired in these cases at a frequency of approximately 1 Hz.

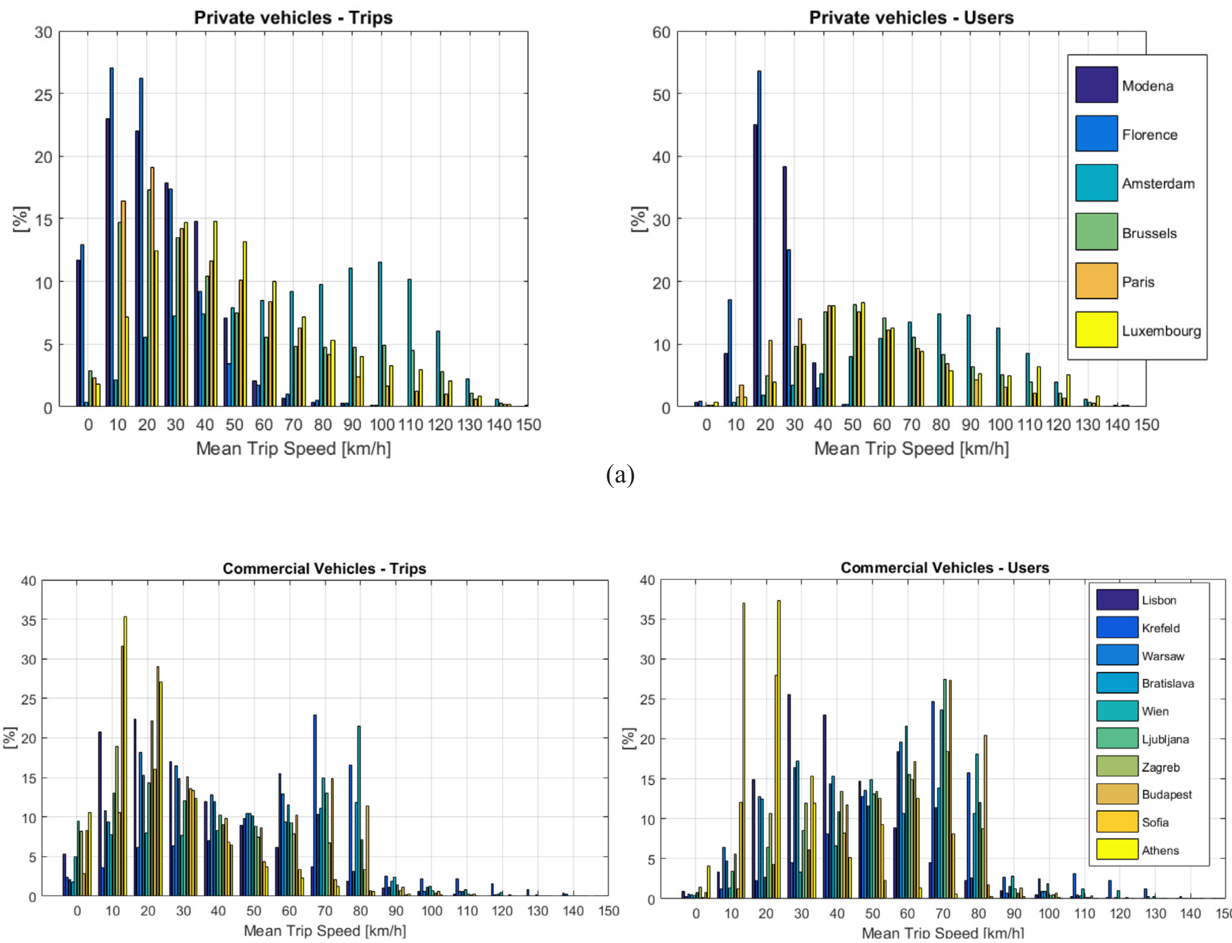
The databases of Modena, Florence, Amsterdam, Brussels, Paris and Luxembourg mainly include private vehicles, whilst the other mainly include commercial vehicles. Monitored private vehicles sum up to 506,105 units, with 1.77 billion GPS records, equivalent to 8.56 million trips and parking events, for a total driven distance of 101.87 million kilometres. Commercial vehicles sum up to 126,081 units, with 0.80 billion GPS records, equivalent to 1.63 million trips and parking events for a total driven distance of 37.7 million kilometres.

The correct pre-processing is a key for harnessing the data potential and its subsequent application. For this reason the raw data has been submitted to a cleansing and consistency check procedure (De Gennaro et al., 2014a), (De Gennaro et al., 2016a) targeted to identify and restore trips affected by non-consistent data series and generic errors of acquisition (e.g. trips not starting with an "engine switch-on" status and/or not ending with an "engine switch-off" status). All the trips with a length less than 30 m and/or duration less than 30 s, not representative of a real mobility demand, are removed in the pre-processing analysis. After this step, the cleansed data is submitted to a data aggregation procedure, to reduce the databases to the records classified per trip, day, week or month (where applicable). This process derives leaner data subsets, particularly useful for handling the large dataset in an effective way with a reasonable computational effort.

2.3. Processing and geo-referencing the data

The data has been processed with module 1 (see Fig. 1) of the TEMA platform (De Gennaro et al., 2016a), to derive the key mobility figures in the different geographical areas, such as, the share of the fleet in motion or parked in the day and in the week in each province area, the average trip distance, trip duration, parking duration, and trip speed and their related probability distributions.

Being the GPS coordinates of the driving and parking events known, the whole data can be geo-referenced and visualised on the map of Europe. In this respect, the data has been dynamically interfaced with digital maps retrieved from the web (Google Inc., 2013). This interface is natively built in the data processing platform of TEMA (De Gennaro et al., 2016a). In order to handle the geo-referenced results, each analysed area is embedded in an analysis window, defined by the minima and maxima values of latitude and longitude, appropriately set as user input to include the targeted area. In this work the whole Europe is considered as embedded in an analysis window extending from 35.7 to 70.7 degrees of latitude north and from −11.8 to 31.5 degrees of longitude east resulting in an area of approximately $15.17 \cdot 10^6$ km^2. The window is divided in squared terrain tiles, concentrating the calculated variables in the centroid of each tile for rendering purposes. The smaller the size of the tile, the higher the resolution of the depicted results; a



(b)

Fig. 6. Mean trip speed share for all trips (left side) and users (right side) for private vehicles (a) and commercial vehicles (b).

terrain tile size of 1 km per edge has been considered, resulting in 15,170,989 tiles for the whole analysis window. Plotting the geo–referenced data it is possible to visualise:

- the map of all the data records regardless of the time;
- a map of the driving patters recorded, cumulative in 24-hours or rendered in time intervals;
- a map of the records of the parking locations, cumulative in 24-hours or rendered in time intervals.

The density of the data points can then be integrated in space in each tile, and used to calculate the daily averaged spatial density over each tile.

Module 5 of TEMA (Fig. 1) is used to estimate the geo-referenced gaseous emissions of the vehicles (De Gennaro et al., 2016a). Three types of emission sources can be calculated: driving emissions, related to the operation of the internal combustion engine during driving phases, cold-start emissions, related to the release of hydrocarbons happening when the vehicle is operated with cold catalyst, and evaporative emissions, related to the release of volatile organic compounds happening when the vehicle is parked. These source analyses can be all handled by TEMA, resulting in a complete overview of the atmospheric impact of road vehicles as derived from their real world driving and parking patterns. Concerning the driving emission sources the grams of pollutant per km are calculated by considering the yearly fuel consumption statistics in the countries for each fuel type (Unione Petrolifera, 2008), (IEA, 2014) and the emission factors as per (European Environmental Agency, 2017), the number of vehicles for each vehicle category registered in the country and the related total km driven per year for each vehicle category as per (ACI, 2011), (EC4MACS, 2016). The classification of vehicles according to their emission control technologies is made on the basis of the legislation they comply with (ACI, 2011), (European Environmental Agency, 2017). The calculated average emissions in g/km for each vehicle type are then scaled up to the province fleet size considering the province fleet share (Eurostat, 2017), (ACI, 2011), (EC4MACS, 2016), (Croatian Environmental Agency, 2013), either of private or commercial vehicles depending on the database.

3. Results

3.1. Mobility results from GPS data versus reference data

Table 2 reports a comparison of mobility data published in different sources and collected via different types of surveys and interviews in Europe and USA, as per (Marconi et al., 2004), (EUROSTAT, 1999–2001), (ISFORT, 2008), (ISFORT, 2015), (ACI CENSIS, 2012), against the mobility results computed from the data presented in Table 1. The comparison is based on the average number of trips per day and on the average distance of the trip. For each reference source the sample size is given if available (i.e. number of households and/or persons involved in the survey). Table 2 reports also the year during which the survey took place. The calculated number of trips per day from the GPS data is slightly higher compared to the average values

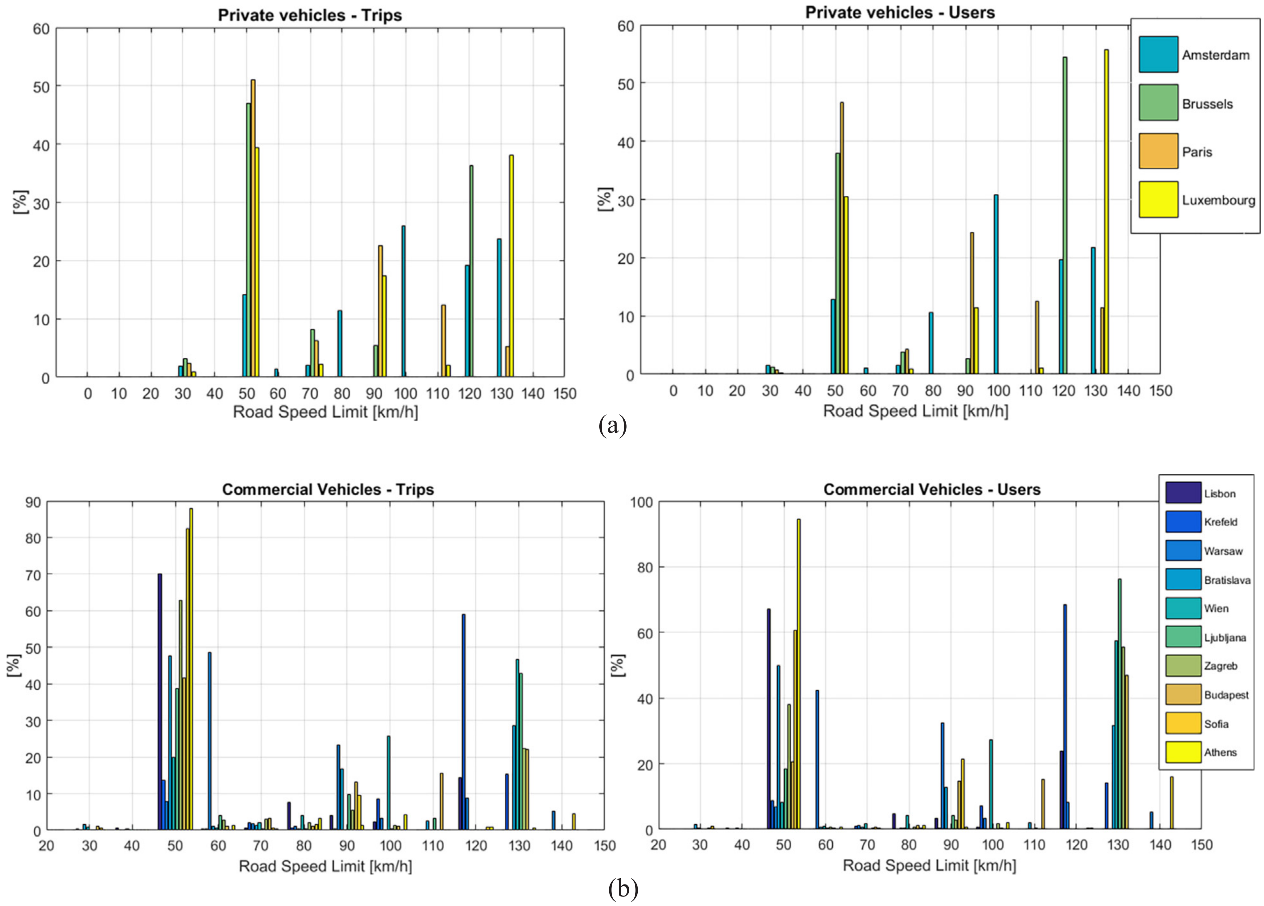


Fig. 7. Road speed limit share for all the trips (left side) and users (right side) for private vehicles (a) and commercial vehicles (b). Data are not reported for Modena and Florence because unavailable.

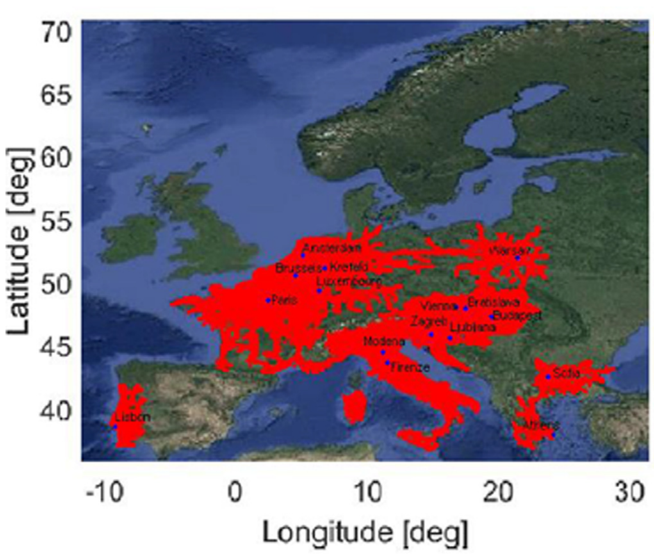


Fig. 8. Map of the data records in Europe.

derived from survey data, while the average trip distance is in some cases lower (Modena, Florence and Brussels) and in some others higher (Amsterdam and Paris). The effect of the different type of surveys undertaken (i.e. geo-coded Computer-Assisted Telephone Interviews, i.e. CATI, face to face or written survey), could explain this difference. The GPS data are, in general, more accurate than surveys data, being based on an accurate sequential sampling of the driving patterns. Survey data can be instead biased by personal evaluations of the interviewed persons which might underestimate short journeys, viewed as insignificant and hence possibly omitted. This is likely to decrease the number of trips per day as well as increase average trip distances being long trips overrepresented and short trips underrepresented. Moreover the trip definition as it is intended in surveys can be different respect to the trip definition assumed in GPS data analysis. In fact a trip is accurately defined as a sequence of engine status in the databases, while in the survey data it can be intended as a movement from a starting to an ending point, independently if one or more short stops occur during the trip itself.

3.2. In-depth analysis of the mobility results from GPS data

Fig. 2 depicts the share of the fleet parked (top) and in motion (bottom) in the week from Monday to Sunday. Fig. 2-(a) focuses on those provinces whose majority of vehicles is classified as private, whilst Fig. 2-(b) focuses on those provinces whose majority of vehicles is classified as commercial. Where more than one week is available in the data, the curve is depicted as averaged on the available weeks. The top and bottom pictures are complementary, i.e. the sum of the parked and in-motion profiles for each city equals to 100%. Both of them are depicted, in order to ease the comprehension of the mobility patterns. The derived mobility behaviour is similar for all databases of the private and commercial vehicles respectively, periodically repeated in the days of the week. Private vehicles exhibits three traffic peaks from Monday to Friday, i.e. in the morning (approximately at 7.30), at noon and in the evening (approximately at 18.30). The peaks are prominent for Modena and Florence, whilst less visible for Amsterdam, Brussels, Paris and Luxembourg which are also characterised by lower activity

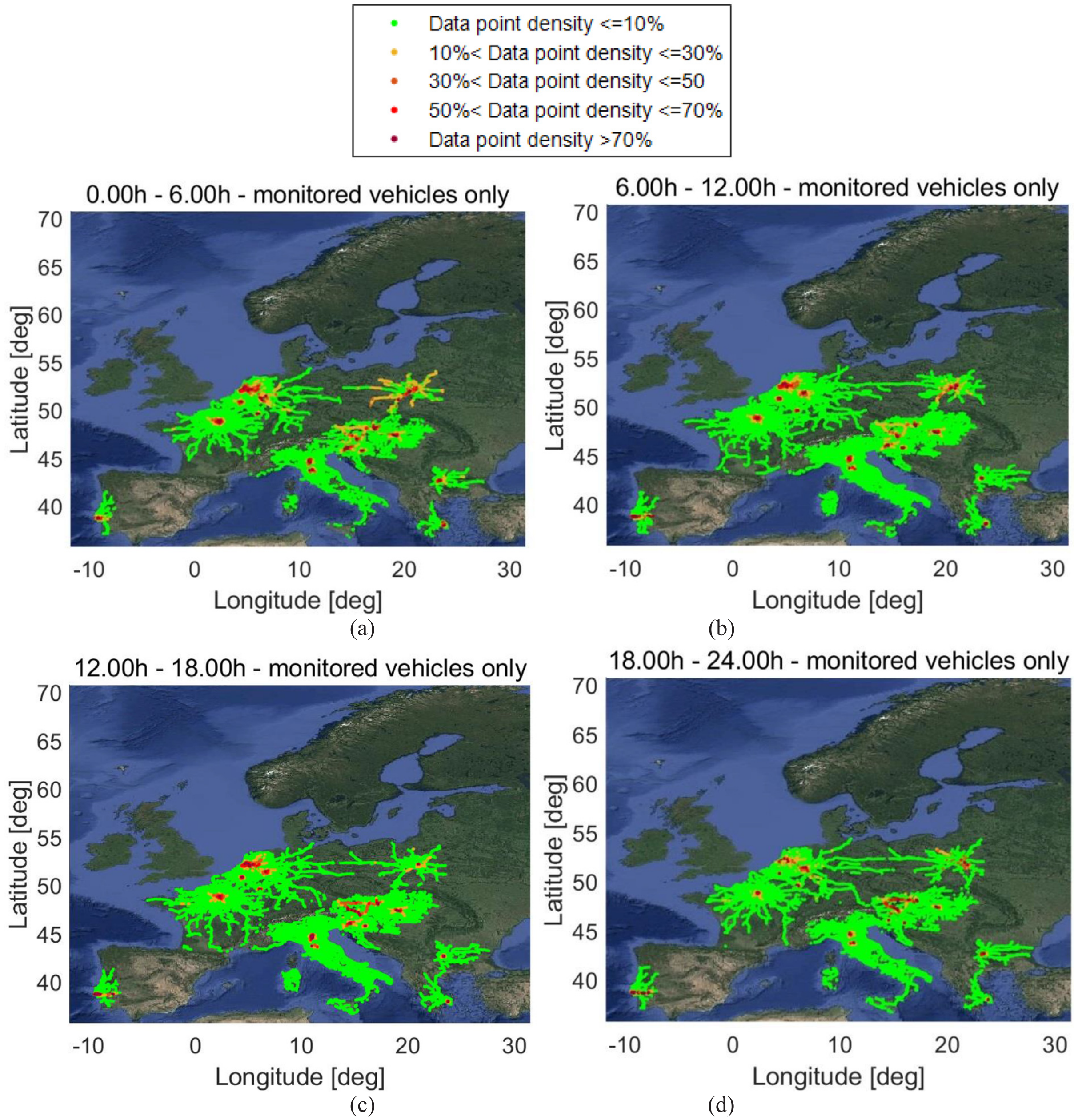


Fig. 9. Averaged density of the driving records per squared kilometre for four aggregated time frame a) from midnight up to 6 a.m. o'clock, b) from 6 a.m. to midday, c) from midday to 6p.m., d) from 6p.m to mid-night. The plot refers only to the monitored vehicles.

levels. The mid peak, in particular, is almost not visible for Paris and Brussels. These differences can be ascribed to the fact that Amsterdam, Brussels, Paris and Luxembourg are capital cities, with more use of public transport services and different professional habits than Modena and Florence, which allow people to shift towards lower shares of adoption of private vehicles and different utility patterns. In the weekend (Saturday and Sunday) the shape of the curves is different, showing mainly two peaks, approximately at 12.00 and at 19.00. Some vehicles are in motion during late Saturday night, although values above 99% of the vehicles are always parked between 1 and 5o'clock in the morning. The share of the vehicles in motion at the same time never exceeds 11.7% of the complete fleet for Modena and 10.4% for Florence, with a mean value of 4.3% for Modena and 4.5% for Florence. It is observed that Amsterdam shows peak values below 7% while Brussels, Paris and Luxembourg well below 5% in line with (Gyan, 2016), (Grolleau, 2015), where it is indicated a percentage of respectively 5%, 17% and 38% for passenger cars, bus and trucks in motion.

Fig. 2-(b) shows the driving behaviour of the commercial vehicles, which, up to a certain extent, looks similar to those depicted for private vehicles. In general, a higher share of vehicles is in motion compared to private vehicles during working days, reaching the 15% peak in Lisbon. The midday drop in number of vehicles in motion is, in general, less visible in the majority of the databases, except for Lisbon that presents a very similar trend to that of Modena and Florence. This suggests that the vehicles are driven without interruption in the working hours of the day, starting between 5.00 and 7.00 in the morning (i.e. earlier than private vehicles) and ending between 14.00 and 18.00. Such behaviour suggests that most of the sample is made of taxis and delivery vans with different working schedules. During the weekend, and especially on Sunday, there is a significant drop of the vehicles in motion, with almost no vehicles driving in Vienna on Sunday. The share of parked fleet is never less than 85% along the hours of the day. Bratislava results to have a small percentage of vehicles in motion in comparison to the other areas.

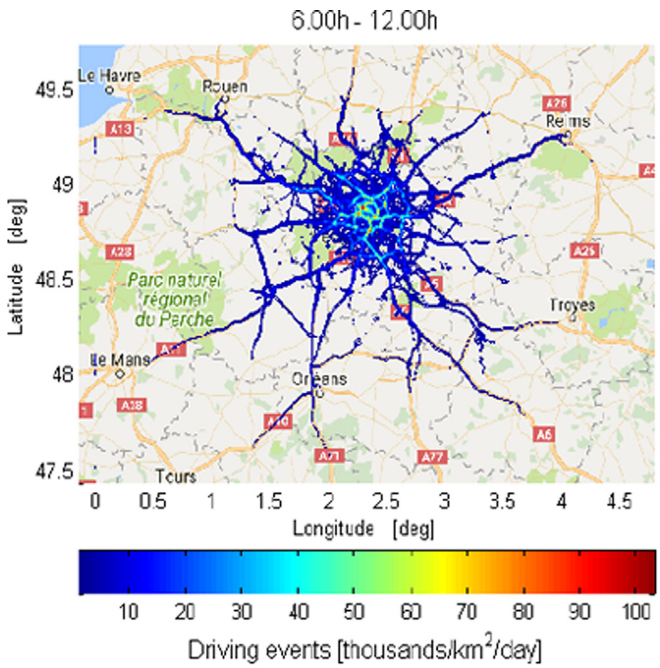


Fig. 10. Zoom of the geo-contours of the averaged density of the driving records per squared kilometre for Paris province from 6a.m. to midday.

Table 3 reports the fleet share per intervals of daily travelled distances. Data are split between private and commercial vehicles. Modena, Florence and Paris show a very similar trend for the trip distribution of private vehicles, with approximately 90% of daily trips being less than 100 km and 110 km respectively. The two Italian provinces show a very similar driving behaviour with approximately 10% of the sample exceeding 100 km/day, reducing to 4.7% and 5.3% exceeding 150 km/day, while more than 50% of the sample travels less than 40 km/day and 75% less than 60 km/day. Concerning Paris 23% of the sample exceeds 100 km/day, while 45% travels less than 40 km/day. Amsterdam, Brussels and Luxembourg show a higher percentage of shorter daily trips in respect to the previous provinces. In Amsterdam 7.7% of the sample exceeds 100 km/day, reducing to 2.4% exceeding 150 km/day, while 58% sample travels less than 30 km/day and 80% less than 60 km/day. In Brussels 18% of the sample data exceeds 100 km/day, while 54% travels less than 30 km/day. In Luxembourg only 2% of the sample exceeds 100 km/day, while 85% drives less than 50 km/day and 62% less than 30 km/day. The different road networks of the analysed areas, as well as the different mobility demands patterns and urban area sizes have certainly an influence on the mobility behaviour observed in these plots. For commercial vehicles, higher percentage of fleet share are observed for longer daily travelled distances, i.e. ≥150 km, in comparison to private vehicles. In Budapest 52.4% of the commercial vehicles travel more than 150 km/day and only 33.2% less than 100 km/day and 16.5% less than 50 km/day. A similar daily travel distance is found for Ljubljana, Krefeld, Vienna and Warsaw, where 41.8%, 40.5%, 36.5% and 33.9% of the commercial fleet travels more than 150 km/day. Bratislava, Athens, Sofia, Lisbon, Zagreb and Vienna show that more than 50% of the commercial vehicles travel less than 100 km/day, with the peak of 94.8% in Bratislava, where high percentages are also found for daily travelled distances less than 50 and 30 km/day. Similar observation can be made for Athens, Sofia and Warsaw, deducing that these vehicles probably correspond to company vehicles, rather than taxis or trucks. However, more detailed information on the vehicles other than the label described in Section 2.2 is not available, and additional verifications have to be carried out in this respect. The values of Table 3 are depicted in form of bar-charts in Fig. 3-(a) and (b), weighted on the vehicle category share per database as reported in Table 1 (i.e. private and commercial vehicles) for a term of comparison.

Table 4 reports the main trip indicators for the analysed data. The averaged trip has a length between 5 and 20 km for the private vehicles and length between 10 and 90 km for the commercial vehicles. The averaged trip duration varies between 10 and 20 min for private and between 20 and 90 min for commercial vehicles, while the averaged parking duration lasts between 2 and 12 h and 24 min and 1 h respectively. Trips speed varies between 26 and 54 km/h for private and between 25 and 65 km/h for commercial vehicles. These values are average values on the full sample available in each dataset. The cumulative distribution functions of each trip indicator are reported in Fig. 4-(a) and (b) for private and commercial vehicles.

Figs. 5–7 depict respectively the bar-charts of the road type share (see legend in Fig. 5-(a) left side), the mean trip speed share and the road speed limit share for trips and users for both private and commercial vehicles. It is noteworthy that trips are driven mainly on major roads, i.e. labels from 1 to 2, with equal distribution on secondary and local roads. Mean trip speeds are mainly between 10 and 50 km/h for private and up to 80 km/h for commercial vehicles, with speed limits from of 50 km/h to 130 km/h, i.e. from city driving to motorway, according to EU common road prescriptions.

3.3. Geo-referenced results from GPS data

Fig. 8 shows the European map of the cleansed database records, reporting 1.56 billion red dots. This map is intended to be purely indicative, aiming at visualising the geographical extension of the analysed databases. Although the data is clearly not exhaustive of the mobility in the EU, it provides a good coverage of significantly different areas characterised by different climatic conditions, i.e. from Mediterranean to Baltic climate, different levels of urbanisation, i.e. rural areas, urbanised areas and megalopolis such as Paris, and different socio-economic conditions. Starting from the southern Europe, it is possible to notice how southern Italy, Greece, Bulgaria and Portugal present a good coverage. Southern European data can be used for focusing the analyses on those phenomena that depends on ambient temperature, e.g. evaporative emissions as per (De Gennaro et al., 2016b). Italy presents a good coverage as a whole, i.e. vehicles that starting from the provinces of Modena and Florence travel across the country, as well as data across the Alps-Danube area, i.e. Austria, Croatia and Bulgaria up until the southern Germany and Poland. A good coverage is also available in the area around Paris, the full Benelux area and the northern Germany.

Going a step further into the geo-mapping analysis Fig. 9 shows the density of the daily records of vehicles in motion per squared kilometre in an analysis windows that focuses on central Europe and aggregated according to given percentage ranges:

- green dots represent a records density per squared kilometre less and equal to 10%,
- orange dots represent a records density per squared kilometre in between 10 and 30%
- dark orange dots represent a records density per squared kilometre in between 30 and 50%
- red dots represent a records density per squared kilometre in between 50 and 70%
- dark red dots represent a records density per squared kilometre higher than 70%.

These density percentage have been derived normalising the number of records in a given square kilometre on the maximum number of records per square kilometre within each considered country. Data are aggregated per time intervals, i.e. from 0.00 up to 6.00 (a), from 6.00 to 12.00 (b), from 12.00 to 18.00 (c) and from 18.00 to 24.00 (d). The higher density of records is found within the centres of the capitals

Table 5
Fleet-weighted CO_2 emission factors in g/km.

		Fleet Category	Fleet share with respect to the total fleet of the country (PC, LDV, HDV, BUS, Mopeds, Motorcycles), [%] (ACI, 2011, EC4MACS, 2016).	CO_2[g/km]weighted on fleet composition
Private vehicles	Province of Modena	gasoline passenger cars	51.3	151
		diesel passenger cars	35.9	
	Province of Florence	gasoline passenger cars	51.4	163
		diesel passenger cars	42.2	
	The Netherlands	gasoline passenger cars	58.1	157
		diesel passenger cars	14.9	
	Belgium	gasoline passenger cars	36.8	165
		diesel passenger cars	43.9	
	France	gasoline passenger cars	37.3	156
		diesel passenger cars	38.5	
	Luxembourg	gasoline passenger cars	39.4	168
		diesel passenger cars	42.3	
Commercial vehicles	Portugal	gasoline commercial vehicles,	1.3	84
		diesel commercial vehicles,	21.9	
		diesel HDV	2.7	
		diesel buses	0.2	
	Germany	gasoline commercial vehicles,	0.4	26
		diesel commercial vehicles,	3.4	
		diesel HDV	1.7	
		diesel buses	0.2	
	Poland	gasoline commercial vehicles,	4.5	75
		diesel commercial vehicles,	7.7	
		diesel HDV	4.6	
		diesel buses	0.4	
	Slovakia	gasoline commercial vehicles,	2.1	87
		diesel commercial vehicles,	7.2	
		diesel HDV	7.2	
		diesel buses	0.4	
	Austria	gasoline commercial vehicles,	0.5	27
		diesel commercial vehicles,	4.7	
		diesel HDV	1.4	
		diesel buses	0.2	
	Slovenia	gasoline commercial vehicles,	0.6	50
		diesel commercial vehicles,	4.2	
		diesel HDV	4.5	
		diesel buses	0.2	
	Croatia	gasoline commercial vehicles,	6.9	70
		diesel commercial vehicles,		
		diesel HDV diesel buses	2.0	
	Hungary	gasoline commercial vehicles,	1.3	62
		diesel commercial vehicles,	9.5	
		diesel HDV	3.6	
		diesel buses	0.4	
	Bulgaria	gasoline commercial vehicles,	2.6	65
		diesel commercial vehicles,	3.2	
		diesel HDV	3.7	
		diesel buses	1.3	
	Greece	gasoline commercial vehicles,	7.8	52
		diesel commercial vehicles,	2.7	
		diesel HDV	2.3	
		diesel buses	0.2	

cities, but peaks change with time during the day, with vehicles moving towards and from periphery in the morning and evening. Fig. 10 depicts instead a zoom in the area of Paris (6.00–12.00 interval) of the geo–-contours of the averaged density of the daily records per squared kilometre, to better appreciate the different shades of colours. The contours show a peak of 100,000 records per km^2 per day (i.e. not vehicles per day) in some streets in the centre of Paris, gradually decreasing while stepping away from the city centre towards the periphery and suburban areas. Similar considerations can be made for the other cities. The high value of records gives the measure of the processing power and capabilities needed to handle such datasets, as well as the accuracy that can be reached analysing the data.

The data has been further processed with TEMA module 5 (Fig. 1) to compute the real-world road driving emissions, as described in Section 2.3. The weighted distance-specific CO_2 emissions in g/km is derived considering the vehicle fleet composition of the country, the total km driven per year (ACI, 2011), (EC4MACS, 2016) and the emission factor for each vehicle category (European Environmental Agency, 2017). Table 5 reports the weighted private and commercial fleet emission factors for CO_2 calculated by applying this methodology.

Note that although distance specific emissions from commercial vehicles are typically four times higher than those from private vehicles, their fleet weighted values results to be lower due to their lower fleet shares. In order to be plotted, the computed weighted CO_2 g/km values reported in Table 5 are:

- distributed over the geo-referenced driving patterns;
- scaled up to the monitored fleet of the province according to the shares reported in Table 1;
- integrated in time over the analysis period of one month or one week depending on the geographical area;
- and finally averaged per day.

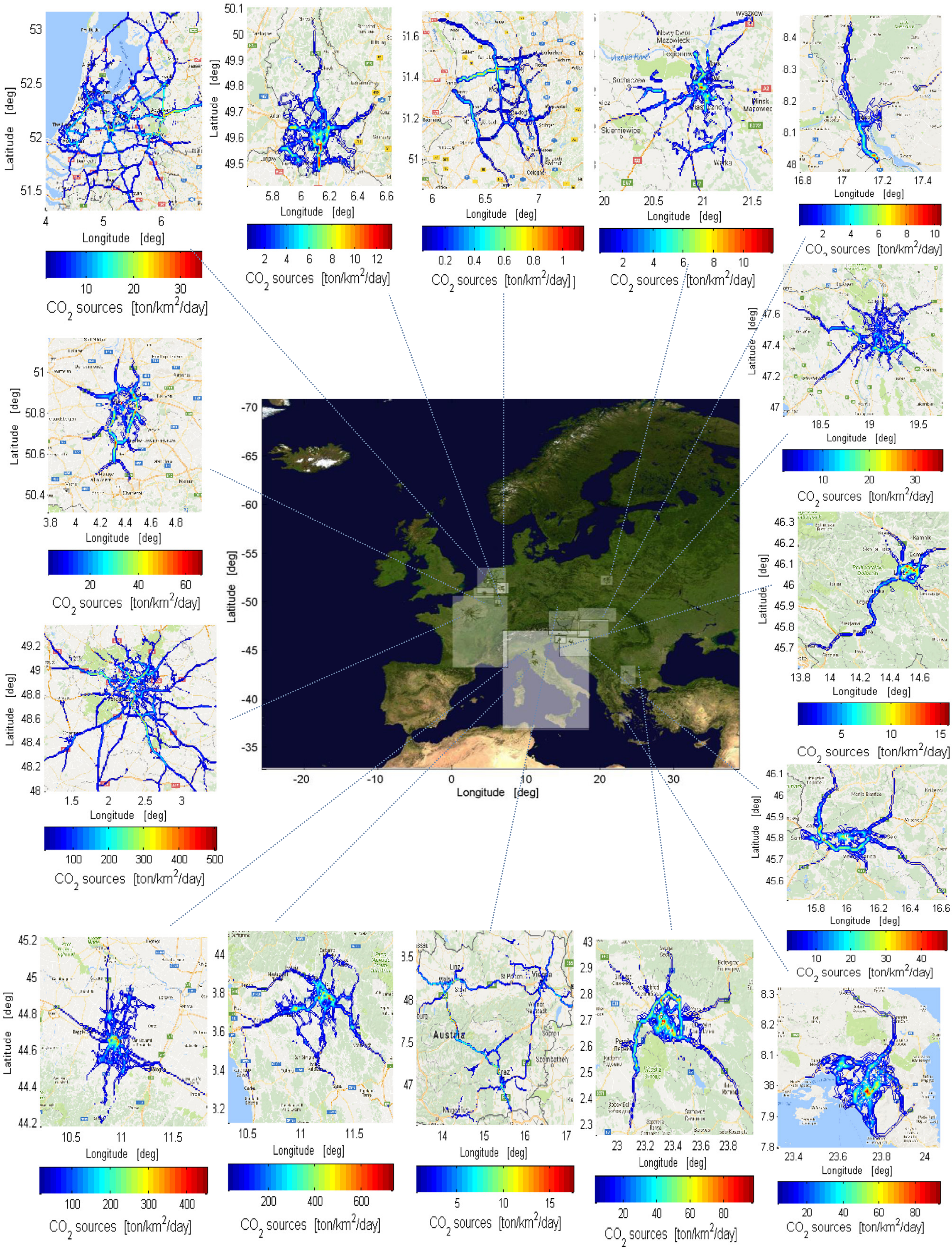


Fig. 11. Geo-referenced European CO2 real-world driving source emissions.

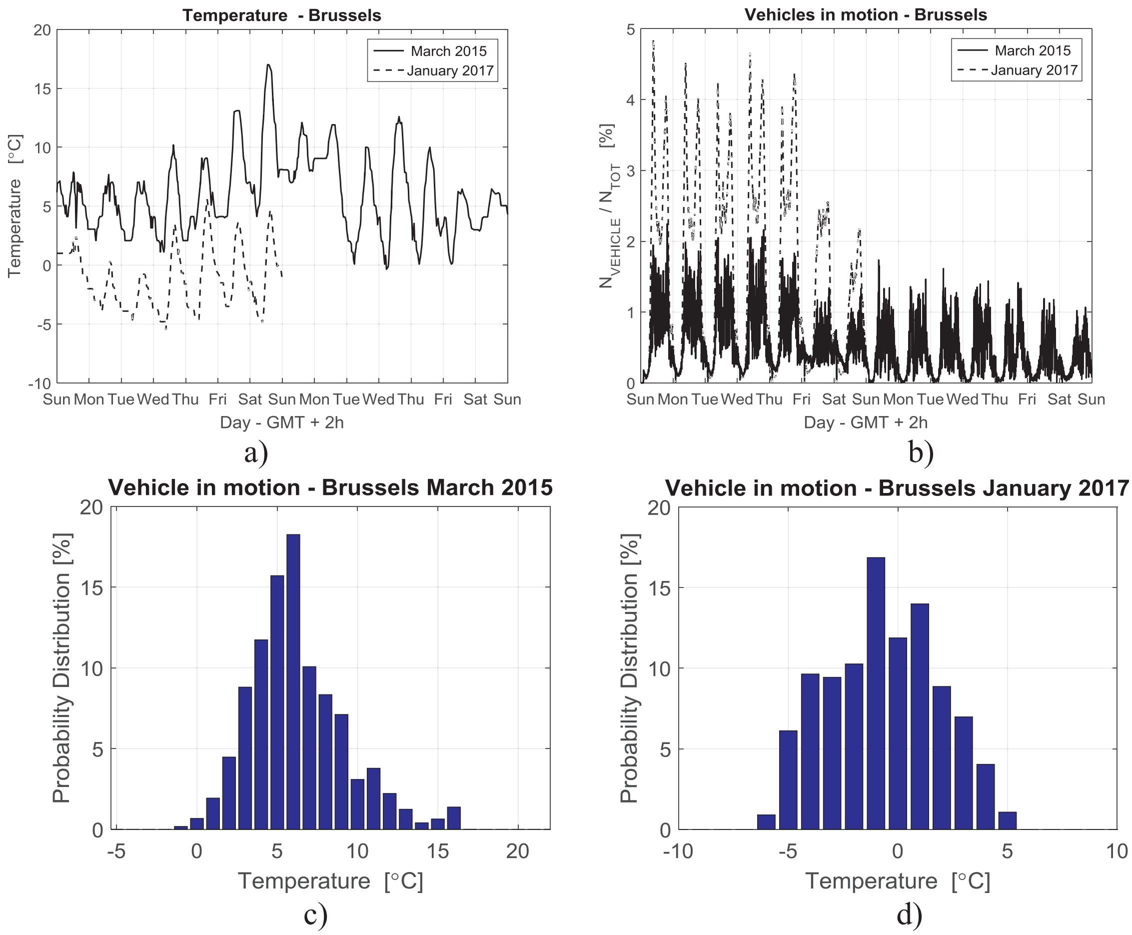


Fig. 12. a) Temperature, b) share of vehicles in motion, c) share of vehicles in motion for experienced ambient temperature in March 2015 and d) share of vehicles in motion for experienced ambient temperature in January 2017.

Fig. 11 depicts the results of this procedure, showing emission sources aggregated from private and commercial vehicles distributed over the major road of the analysed areas, with peak values above 500 tons/km^2/day in Paris, Modena and Florence. The average value per road results to be between approximately one-third and one-fifth of the peak value. Sources are higher around city centres, gradually decreasing at the country borders, consistently with the driving data distribution. The results refer to the monitored urban fleet share of the given province; a low number of monitored vehicles in the database will result in a low emission source value for square kilometre and day. The vehicles driving through the geographical area but not registered in the country are not considered in the calculation.

It is noteworthy that most of the capital cities show the highest value in proximity of their centre, except for Amsterdam probably due to the high use of bikes in the city centre (Eurostat, 2004) and Brussels that shows the highest emissions on the ring around the city. In Vienna the highest emissions are found on the motorway arteries running around the city and heading towards Graz; however this distribution is due to the data, mainly referred to commercial vehicles. The density of the vehicles in motion across a country varies from country to country and within the country itself generating higher values of CO2 per km only where the concentration of the sources is high. In order to properly compare the emission source plots among the considered areas, a normalisation with respect to a reference number of vehicles needs to be made. Beyond CO_2 other emissions and pollutants, such as carbon monoxide, nitrogen oxide, hydrocarbons and particulate matter, can be depicted in the same way.

3.4. Ambient temperature and mobility

A target analysis has been carried out to assess the vehicles in motion in relation to the seasonal variation of the temperature. To this purpose another set of data referred to Brussels has been considered, recorded during a cold week in January 2017 (Be-Mobile, Traffic and Mobility, 2016) (Universalis, 2016), the coldest month of that year. The set refers to 95,383 monitored vehicles and 16.5 million km and 396 million data records. The 90.4% of the data refer to private vehicles.

Fig. 12 shows the temperature variations for the two sets from Brussels province for March 2015 and January 2017, together with the share of vehicle in motion in the monitored weeks. It is observed that a higher percentage of vehicles in motion (approximately double) is observed for January in respect to March. This might be related to winter season travelling. Analysing further these results it is possible to derive the distribution of vehicles in motion in function of the temperature experienced in the monitored weeks as shown in Fig. 12c) and d). More than 15% of the monitored vehicles experienced a temperature of 6 °C in March and −1 °C in January, while up to 65% of the monitored vehicles experienced a temperature below 0 °C in January and 57% above 5 °C in March. These results can support target analyses for transport policy assessment, similarly to the study carried out by the authors for the evaporative emissions assessment from parked vehicles in the summer season (De Gennaro et al., 2016b) or sun irradiations on parked photovoltaic roof vehicles for eco–innovation technologies assessments (Lodi et al., 2018). These analyses can also support the assessment of the impact of geographical and temperature differences on electric vehicle driving range due to cabin conditioning energy consumption and road gradient. The increase in the energy consumption and related driving range reduction due to the use of the Heating, Venting and Air Conditioning (HVAC) system vary in fact with the ambient temperature; approximately -60% driving range reduction at −10 °C, −42% at 0 °C, −27% at 10 °C, −5% at 20 °C and −22% at 40 °C [58]. This implies possible differences among the results for different geographic areas in relation to their typical seasonal temperatures. Concerning conventional fuel vehicles, the use of the HVAC system can increase the fuel consumption up to 20% (Government of Canada, Natural Resources Canada, 2016) depending on the vehicle's interior size, the outdoor temperature and other operating conditions. Analysing Europe as a whole, a different temperature can be observed in the weeks in which the data has been sampled. For instance, in the first week of March 2015 the average minimum temperature was around 0 °C (World Temperatures, 2017) in Amsterdam, Brussels and Paris, while in the same week in Athens the average minimum temperature was 10 °C. Moreover, the average maximum temperature was 9 °C in Amsterdam, 14 °C in Brussels, 12 °C in Paris, 16 °C in Athens, thus suggesting a possible different behaviour in the use of the HVAC system in these areas that can be further explored to assess the impact on the energy and fuel consumption of different vehicle technologies.

4. Conclusions and possible future applications of big data in support of transport policies

This work presents the earliest results achieved by using TEMA for processing European-wide mobility data. In respect to previous studies from the authors which focused on the Italian provinces of Modena and Florence, here fourteen additional regions have been included in order to extend the data coverage to a continental scale. These are: Amsterdam (NL), Brussels (BE), Luxembourg (LU), Paris (FR), Lisbon (PT), Krefeld (DE), Warsaw (PL), Bratislava (SK), Vienna (AT), Ljubljana (SI), Zagreb (HR), Budapest (HU), Sofia (BG) and Athens (GR). The complete dataset accounts for approximately 2.57 billion records, 139 million driven kilometres and 632,186 monitored vehicles, of which 506,105 associated to private vehicles, and the remaining 126,081 associated to commercial vehicles. The paper presents the data as a whole, focusing on the efforts needed to pre-process and aggregate it in a usable format.

Mobility results are presented per each database and compared with reference statistics, deriving average values and cumulative distributions for trip distance, trip duration, parking duration and trip speed. The analysis shows that the share of the private fleet in motion at the same time never exceeds 12%, with some areas with less than 5% vehicles in motion, while the commercial vehicles show in general a higher share of vehicles in motion in respect to private vehicles, up to 15%. The data has been rendered on the European map for visualising its geographical coverage and then represented as plots of the spatial density of the records. Module 5 of TEMA has been run to depict the geo-referenced real-world emission sources associated to the driving data, presenting a possible application of the platform on such vast data.

The large scale European mobility analysis presented in this work could support a critical analysis of the major dynamic changes that could affect the demand for travel and related transport systems in future and depict opportunities to shape the next generation of transport policies towards a zero emission society. Crossing all the information about the mobility needs, population density and geo-distribution and urban orography dedicated multi–modal interconnected services could be defined tailored on people mobility, supporting a transition towards mobility as a service. Crossed border travel data analyses could be useful to support the deployment of e-corridor for trucks or other innovative technologies for freight transport but also for passenger electric vehicles.

The presented work constitutes a first attempt for a continental scale pilot study of travel behaviour in Europe, with the aim of showing how the presented data and processing methodologies allows for unprecedented opportunities to shape the next generation of transport policies to meet the existing and future challenges of the transport systems.

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