Transportation Engineering 21 (2025) 100355

Contents lists available at ScienceDirect

Transportation Engineering

journal homepage: www.sciencedirect.com/journal/transportation-engineering

Matching demand and supply in motorised mobility: A data-driven differentiation of the driving patterns for urban contexts

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ARTICLE INFO

Keywords:
Electrification
Internal combustion engines
Driving scenarios
Urban and non-urban
Emissions

ABSTRACT

This paper deals with future automobiles and their actual compliance with both local and global emissions: the European Parliament's deliberation on the 100 % reduction of locally measured CO_2 emissions (February 2023), on newly manufactured vehicles by 2035 clearly and plausibly expresses a concept - oriented towards the transport supply - that needs to be completed.

The current scenario for climate change requires actions for both mitigation and adaptation. The transportation sector is currently one of the sectors where mitigation actions can be applied. This is the scope behind the program Fit for 55 led by the European Parliament, which would like the reach of net zero CO_2 emissions by 2035. Additionally, many cities have applied for the net zero emission challenge by 2030. All this creates an intricated scenario for the private transportation sector, which should be affordable and flexible for all the transportation needs.

A way to reach the goals defined above is the spreading of electrified transportation, including:

BEVs (Battery Electric Vehicles), which provide zero tailpipe emissions during use,

PHEVs (Plug-in Hybrid Electric Vehicles), which can do the same just when and where needed, without compromising the freedom of movement that drivers are accustomed to.

One of the solutions for reaching these goals is the adoption of electrified vehicles. Nonetheless, many limits hinder a massive spread of BEVs, like energy and resources availability, queuing phenomena at public accessible charging stations, fire-load limitations, serious depreciation on second hand market, besides actual environmental sustainability: when looking at the carbon emissions footprint on the entire lifecycle of the energy source (namely, Well To Wheel) and of the vehicle (LCA), the neutrality with respect to GHGs is challenged.Based on these assumptions, the scope of the paper demonstrates systematically that it is possible to consider differentiated powertrain solutions per driving scenario, namely for urban contexts, thereby enabling the proper exploitation of each technological solution.

1. Introduction

A vehicle which can use electric traction when and where needed evidently produces no local tailpipe emissions in those specific situations: this perfectly fits urban driving, where concerns about local pollutants from vehicle traction are especially important.

Urban driving is typically characterised by short trips, low and variable speeds, frequent stops and accelerations from a standstill as well as long idle times. In these conditions, such a flexible vehicle performs very well.

On the other hand, an electric vehicle may struggle with longer trips at higher speeds, which are more common outside urban areas, where requirements for pollutants and noise are generally less strict.

In such non-urban scenarios, a conventional powertrain, better if powered by alternative fuels, plays a pivotal role, since its fuel consumption efficiency is benefited by higher and more constant travelling speeds, and allows to concentrate the use of electric traction in the urban contexts, being the spread of BEVs on an extended market evidently limited. The European Parliament's deliberation on the 100 % reduction of locally measured CO_2 emissions (2.2023)[1] has generically referred to any application, but evidently it needs to the completed from the physical and chemistry viewpoints.

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[1] 2021/0197(COD) - 14/02/2023 - CO2 emission standards for cars and vans (europa.eu)

https://doi.org/10.1016/j.treng.2025.100355
Received 30 December 2024; Received in revised form 31 May 2025; Accepted 2 June 2025
Available online 18 June 2025

In order to validate this idea, a statistical driving cycle is generated, whose aim is to adopt its use as a tool in a more complex data-driven policy.

The aim of this work is to demonstrate that, with a systemic approach, it is possible to pursue different solutions beyond pure electrification, as it could not fit all use cases that are present.

A vehicle with electric capabilities (Plug-in hybrid electric vehicle or PHEV, battery electric vehicle or BEV) would find its best application in the cities, where average speeds are low, frequent stops occur, and trips are short, with interspersed short and long idle periods. Instead, a vehicle equipped only with an ICE (internal combustion engine) would struggle because the engine would be running far from its optimal efficiency area, resulting in higher emissions.

On the contrary, in extra urban scenarios, where the travel speed is usually higher, less stops occur and the trips last longer, a vehicle powered by an ICE has a better behaviour, even winning - from the overall efficiency point of view - when compared with an electric one.

Mobility habits have changed throughout the years, and transportation has followed, needing to adapt to the changing demand. However, this cannot happen freely: impact of transportation on the environment must be taken into consideration, especially when dealing with the climate change global issue. Transport modes all-together were responsible for approx. 21.1 % of the global CO_2 emissions in 2023, as reported in [1]; within them a variable, yet anyway significant, role is attributed to road vehicles.

Different actions have been carried out in recent years, including fostering modal shift from private to public transport or light mobility, when possible, but private transportation remains a pillar of mobility for a great part of the population.

Regulations aim to fight GHG (greenhouse gas) emissions from transportation [2] and one of the requests sustained until the in questioning - from the end of 2024 - deliberation is that, from 2035, any new registered vehicle should emit zero greenhouse gases (GHG) during use. But where? A way to fulfil such request is evidently to promote electrification in transportation, which does not imply full electric vehicles. There are indeed several limitations to a massive spread of full electric vehicles, like availability of electric power, availability of charging stations, the relevant increase in recharge time, the actual range even at low and high temperatures, serious difficulties to move an electric car if stopped for low SOC (state of charge), cost of rapid and fast charging, fire load in garages, besides the total cost of ownership. Outside from the micro and macro economical and technical viewpoints, at global level also the need for rare and specific raw materials provides a significant limitation.

Moreover, only switching to BEVs does not ensure lower GHG emissions compared to an ICE vehicle. In fact, the electricity production process and actual usage on board besides the energy management of the batteries must be considered to assess whether BEV reach GHG neutrality or not.

From a homologation standpoint, EURO 7 regulation has been published in 2024 [3] and executive from July 2025. It considers vehicle cooperation and it includes the same limitations in terms of GHG as its predecessor (EURO 6), but it even opens the opportunity to consider emissions as *net zero*, broadens the limits on particulate emissions from brake and tire wear and imposes restrictions on the state of health of batteries.

The high TTW (tank to wheel) performance of the BEV does not necessarily correspond to lower emission values, both in terms of GHGs and pollutants, than other types of vehicles, which may therefore give the same outcomes in different ways. From the point of view of road transport and its electrification, in short, the global problem of the GHG effect, which is partly attributed to transport, is not necessarily solvable by adopting an energy carrier such as electricity stored in a battery (i.e., within a BEV), as it is necessary to be cleared how that energy is produced, as well as the energy storage component (i.e. the battery), besides the overall efficiency of the production of the vehicle itself. Therefore, how the vehicle is used must shape its choice and its design.

In this paper, an analysis of all the variables to be considered to match transport supply and demand is performed in section Material and Methods. The investigation has the objective to highlight the key elements that characterise each powertrain and driving scenario to promote a better compatibility between the two groups.

Additionally, a list of the legislations concerning air quality and GHG emissions is provided.

Then, the methodology that has been applied is described in section so titled; a deep dive in the data that have been collected is performed and the basic theory behind the clustering method that has been applied to the data is shown.

In the Results section, the outcome of the clustering methodology is explained, giving space to the opportunities highlighted in the Discussion section.

2. Material and methods

2.1. Legislation

Over the past decade, the European regulatory landscape addressing air quality and GHG emissions from transport has evolved significantly, reflecting both heightened environmental ambitions and the complexity of the challenges involved. Central to this framework is the progressive tightening of pollutant limits for ambient air, as well as the establishment of increasingly stringent requirements for vehicle emissions and fuel quality. For instance, the European Union has set clear targets for the deployment of alternative fuels infrastructure, aiming to facilitate the transition to cleaner mobility options and reduce the sector's dependence on conventional fossil fuels [4]. In parallel, air quality standards have been revised and reinforced [5,6], with the most recent updates introducing lower permissible thresholds for key pollutants and, for the first time, specifying penalties for non-compliance. These measures are complemented by directives focused on the promotion of renewable energy in transport (RED, REDII), which set binding targets for the share of renewables in the sector's energy mix and specifically require that 14 % of the energy used in EU transport must come from renewable sources by 2030 [7,8]. They also encourage the diversification of energy sources and the adoption of innovative propulsion technologies. Fuel suppliers are now required to actively reduce the carbon intensity of their products, aligning with broader efforts to decarbonise the entire supply chain [9]. At the vehicle level, manufacturers face strict limits on average CO_2 emissions from new passenger cars [2], with mechanisms in place to encourage collective compliance and penalise excess emissions. Furthermore, the regulatory regime has expanded to encompass real-world driving conditions [10,11], mandating the use of portable emissions measurement systems to ensure that vehicles meet emission standards not only in laboratory tests but also during everyday use. These comprehensive policies are underpinned by the European Strategy for Low-Emission Mobility, which articulates ambitious goals for GHG reduction and promotes the uptake of very low-emission and zero-emission vehicles through a technology-neutral approach. Despite this robust and multi-faceted framework, it is important to recognize that current regulations remain focused on emissions generated during the use phase of vehicles, specifically tailpipe emissions, without yet extending impacts of transport technologies to the full lifecycle. This tail-pipe focused approach generated the push towards electrification as the best solution.

However, the legislations mentioned until now highlight both the progress achieved and the ongoing need for a holistic approach to achieve sustainability in the mobility sector.

In parallel to private mobility solutions, new proposals for promoting the shift to sustainable mobility have been carried out with the frameworks Horizon 2020 and Horizon Europe. In particular, the project MaaS4EU aimed at promoting the adoption of MaaS (Mobility as a Service) to foster modal shift towards a combination of mobility solutions (both public and shared) that has the goal to provide a flexibility as close as possible to the one that private transportation intrinsically has.

However, private transportation remains a big component of the modal share for mobility. In fact, it represents 60 % of the modal share in Italy and it accounted for 73 % in the European Union in 2022 [12].

2.2. Technical standards to address emissions

Being the automotive landscape mainly dominated by conventional and more polluting vehicles, given their exponential spreading in the previous three-four decades, regulations for containing for first local pollution and, some years later, GHG emissions became necessary starting from 1990s. Over the years, EURO homologation standards were released (1993 for Euro 1 and I), requiring vehicles to emit less pollutants during their use; EURO VII represents the last update of such standards, released in April 2024, and into force from July 2025 [13]: with respect to its predecessor, it considers not only the emissions from the tailpipe, but also emissions from tyres and brakes.

Introducing such regulation, EU forecasts that NO_x emissions will be indicatively reduced by 35 %, particles from the tailpipe emissions will be reduced by 13 %, and particles from the brakes will be reduced by 27 % [3]. For what matters hybrid vehicles and BEVs, the regulation increases the standards for battery durability requirements.

In addition, it specifies that vehicles can make use of technologies such as geofencing, that enable the so called V2I (Vehicle to Infrastructure) of vehicle to the cloud connectivity to achieve homologation standards.

A small note regarding emission neutral fuels is made too, since the regulation specifies: "*Where the Commission makes a proposal for the registration after 2035 of new light-duty vehicles that run exclusively on* CO_2 *neutral fuels outside the scope of the* CO_2 *fleet standards, and in conformity with Union law and the Union's climate-neutrality objective, this Regulation will need to be amended to include the possibility to type-approve such vehicles*".

At present, conventional vehicles do not fit into such scenario, since emissions during their use are the element that classifies the vehicle as a good or a bad actor in terms of climate neutrality; moreover, possible CO_2 neutral fuelled vehicles are considered as non-contributors to the fleet goal.

The goal of this paper is to expand the view from the pure use of the vehicle to the entire cycle that the energy carrier follows from the primary source until it is made available on board: in other terms, we need to look first at the entire Well To Wheel energy chain (WTW).

A first step can be made in terms of energy efficiency: according to the study [14], a BEV is less efficient than a conventional vehicle in the Well To Tank (WTT) part of the chain. This is shown in Fig. 1 from the same study.

Additionally, for an electric vehicle, the CO_2 emissions related to the production mix for the electric energy is highly dependent on the geographic area of interest: in 2022, in Europe, CO_2 emissions were calculated to be 258gCO_{2eq}/kWh [15].

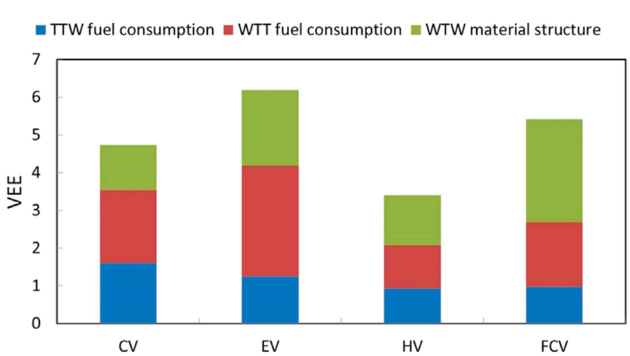

Fig. 1. Lifecycle WTW vehicle energy efficiency for Conventional Vehicles (CV), Electric Vehicles (EV), Hybrid Vehicles (HV), Fuel Cell Vehicles (FCV).

Considering indicatively 3.6 to 7 km per kWh for a pure electric vehicle - without considering the thermal management of the battery neither air conditioning on board - it would mean that, recharging the battery with the European electricity mix, the vehicle would emit approx. 50 g$CO_{2\ eq}$/km from a WTW point of view.

According to the IVL Swedish Environmental Research Institute [16], one has to consider 50 g$CO_{2\ eq}$/km of emissions only for the manufacturing of the battery in the USA.

For conventional vehicles, according to [2], the emission limits will tighten over the years, moving from roughly 110 g/km in 2021 for the EU fleet (already adjusted to the introduction of the WLTP harmonised homologation procedure), to a decrease of 55 % in 2030, reaching 49 g/km. In 2035, the limit for the fleet has been set to a net 0 g/km of CO_2 emission [17], however just considering the vehicle usage, for the time being. How could this goal be achieved in less than ten years?

In 2022, about 49 % of the barrels of crude oil used in the world were used by road transport [18] - while transport systems as a whole normally exceed 60 % of the whole consumption of oil-derived fuels) - meaning that transportation requires, on a daily basis, about 85TWh of energy.

The current state of the regulations does not leave the proper space to conventional or hybrid powertrains after 2035, because their GHG emissions at the tailpipe will still inevitably be above zero, although envisaging a record of 9 gCO_2/km for new PHEV in 2025 [19]. Focusing only on the TTW aspect, the zero goal would be feasible only if carbon was removable from the vehicle: in the world there is no liquid fuel, at normal temperature, not containing carbon and, being transport systems mobile by definition, it is necessary to reach any vehicle operating in any location with a portable liquid fuel.

As well known, *de-carbonisation* implies eliminating carbon from the energy source: for a number of sectors of our society, this is gradually possible, albeit very challenging, because they make use of an energy distribution network that can therefore implicitly differentiate between upstream energy sources.

However, transport systems not operating on fixed guideways, by definition, need to be detached from any energy distribution network. Therefore, storing energy on board, refillable anywhere, is an unavoidable step that needs to be addressed.

Consequently, the only feasible solutions fall within one or more of the following options:

- people moving less, reduced logistics for freight (hence, less energy needed) and both transported in a more aggregated way (e.g., public transport and electricity for transport systems on fixed guideways);
- the remaining vehicles (not operating on a fixed guideway) have a tank on board containing a liquid combustible at ambient temperature, because pressurisation and changes of state (generally from gaseous to liquid) imply energy expenditure that worsens the efficiency of the energy chain. There is no efficient liquid fuel in the world at ambient temperature that does not contain carbon at the time the research was conducted. At the same time, it is possible to produce liquid fuels that, while emitting GHG like carbon dioxide as a combustion by-product, are obtained from either biological (biofuels) or synthetic processes (e-fuels) that absorb CO_2 from the atmosphere, making the overall energy chain (i.e., WTW) climate-neutral or even carbon dioxide-negative.

Thereafter, in transport and mobility - as alternatives to crude oil derivatives are being pursued, such as hydrogen (as a fuel or energy carrier), methane, biofuels, e-fuel, etc. - it is perhaps more appropriate to speak of *de-fossilisation*, because carbon will not be easily removed for vehicles moving detached from the energy distribution network.

The case of urban (or other delimited areas, e.g. LTZs or environmentally protected areas) transport is different: in such areas, local de-carbonisation can be pursued, knowing that actions taken locally are not sufficient to affect the overall net carbon balance. Overall decarbonisation requires a holistic approach that considers the entire cycle of the energy carrier.

This means that one of the solutions would be a carbon-free fuel, like ammonia or hydrogen, providing several challenges, including the shift to a fuel that is non liquid.

However, focusing only on electrification brings several challenges too. For instance, shifting the entire current vehicle fleet to BEVs would mean a drastic increase in the demand of electric energy. In numbers, in 2022, 28,660 TWh of electric energy was produced globally [20]; based on the energy from fossil fuels that is used currently on a daily basis for transportation, that is 85 TWh, one can see that roughly a 100 % increase of the electrical energy generation would be needed (the electric motor consumes indicatively 1/3 of an ICE, yet we need to consider the production and distribution of the electric power): it is true on one side that the average efficiency of the electric motor would abate the final consumption of electricity yet the power supply for rapid and fast charging implies an availability of both power and energy that is amplified with respect to the apparent reduction of BEVs absorption on the grid.

Furthermore, if there is enough electricity to power all electric vehicles that are present in the market, there would not be a guarantee that the additional power generation request would be satisfied without making use of fossil sources. On the contrary, as highlighted in [21], this would most likely lead to an increase in the emission intensity because the marginal grid mix, up to now, has relied on fossil fuels. Nevertheless, electrification also opens up innovative opportunities for supporting grid stability and optimizing energy use, for example through vehicle-to-grid (V2G) services that leverage the unused capacity of parked electric vehicles to supply energy back to the grid, as demonstrated by recent research using real-world mobility data to identify optimal V2G locations and quantify their potential benefits [22].

2.3. Private mobility demand

To assess what actions can be considered, it is important to understand the private mobility demand. It can be observed that the mobility habits of people in Europe - but also in the USA with slightly greater distances - have a hyperbolic trend: according to different studies of the Italian mobility trends, analysed in [23], when comparing the number of trips with the distance that is driven on a daily basis, the most frequent trips are the ones with the lowest driven distance, and the frequency of the trips decreases as the driven distance increases, with an average distance that spans between 32.1 and 38.7 km/day. The results can be seen in Fig. 2.

On top of this, other studies have been performed to analyse the shape of the private mobility demand in Europe based on real data, assessing the frequency of length and time of the trips, seen as single or on a daily basis. In study [24] it can be observed, considering the distances that are driven, that the urban trips length is <5 km for 35 % of the entire data, and <10 km for 90 % of the entire data. Additionally, the most frequent distance covered in a single trip (one way) is 5 km.

In general, though, cars allow for a variety of trips to be covered; in fact, in the non-urban context, 90 % of the extra-urban trips are shorter than 30 km, with one-way peaks at around 10 to 30 km. In motorways, instead, trips result to be much longer: only 10 % of the trips are shorter than 20 km, 35 % are between 20 and 60 km long, and 55 % cover >100 km.

The same study analysed the time spent travelling on a single trip in the urban context. Data show that >50 % of the journeys last <16′, 90 % <52′, and 99 % <1h47’.

From the same data, one can also see that, depending on the trip context, the composition in frequency changes. In fact, 40 % of the urban trips was shorter than 5′, >50 % of the extra-urban trips was shorter than 30′, and slightly <80 % of the motorway trips last >30′, as can be seen from Fig. 3.

Other aspects related to daily routines are taken in consideration. According to [25], taking the case of a metropolitan city as Turin, in the centre it is common to have short stops between two consequent trips (usually less than three hours), while in suburban and residential areas two consequent trips may be separated by longer stops, generally being parked overnight. This habit offers an opportunity to define charging slots for battery-electric vehicles (BEVs or PHEVs), since it takes several hours to complete the recharge operation at low power. In addition, from [24], data show similar results: 50 % of the urban trips present an idle time before the next trip that is shorter than 30′, and 20 % goes from 30′ to 2.5 h; instead, 55 % of the extra-urban trips present an idle time before the next trip that go from 0 to 2 h and 20 % goes from 2 h to 4 h. Motorway scenarios present longer stops between trips, where 50 % of the stops is <1 h, and 20 % is between 1 h and 4 h.

As mentioned above, longer stops between two trips allow to allocate charging slots for BEVs or PHEVs, but this needs to be correlated with the power depleted during a single trip.

On this last aspect, the Communication to the EU Parliament [26] says that "[…] the ultimate objective is to allow a car to travel across Europe, making electric vehicle charging as easy as filling the tank"; at the same time, from [24] it emerges that, unless fast charging stations are present, a large proportion of those who drive 100 km per day will not have the possibility to recover all the energy consumed by means of a 3 kW typical domestic charging spot, that is - at the present day - the most economically convenient solution, allowing to have shorter break-even points when compared to conventional ICE vehicles.

Moreover, as shown in the same study [24], although the majority of the trips is short in distance, the stops are not sufficiently long to have the xEV fully recharged, especially in areas where the installation of

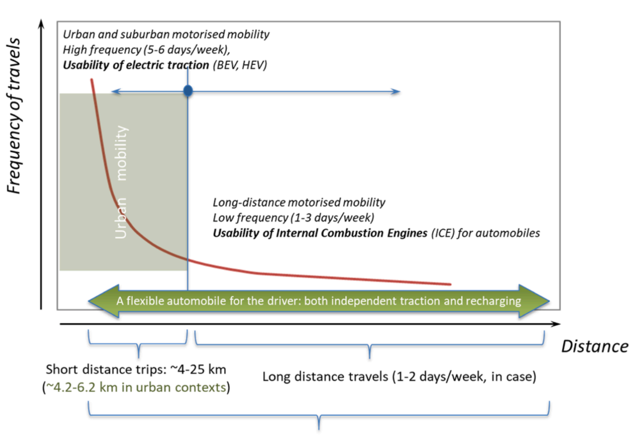

Fig. 2. Average distances travelled in Italy according to different studies.

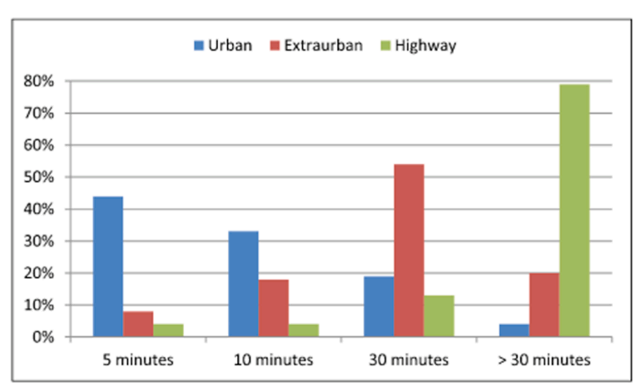

Fig. 3. Frequency of the duration of each trip, divided per context of use.

charging stations is easier.

The variables that influence the demand for transportation, and by consequence the choice for a vehicle, include also environmental sustainability - which is becoming an increasingly pervasive concern in the population, also thanks to ICT technologies [27] - and social sustainability - which means putting together practices to ensure equity within society.

In this context, urban planning strategies play a crucial role in shaping mobility demand and supporting sustainable transport choices. As demonstrated by Cirianni and Leonardi [28], shifting long-term parking to suburban or fringe areas and implementing “push-pull” measures (such as discouraging car use through parking charges and time restrictions in central zones, while simultaneously improving public transit and pedestrian infrastructure) can optimize the use of existing road space, reduce congestion, and promote walking and cycling. Their findings show that such integrated parking and mobility policies not only reduce the negative externalities of urban traffic (like pollution and congestion) but also improve accessibility and quality of life in city centres, without needing to expand road infrastructure or parking supply. These approaches are particularly effective when revenues from parking schemes are reinvested in sustainable mobility initiatives, further reinforcing the shift towards greener and more efficient urban transport systems.

It is therefore necessary, in addition to considering a serious and comprehensive information campaign towards users, to implement practices that help users make an informed choice without denying them the ability to choose some alternatives over others for solely economic reasons. To achieve this, subsidies for sustainable mobility, such as tax exemptions for the purchase of Very Low Emission Vehicles (VLEVs) to lower the upfront economical investment, are put in practice in many countries in Europe. These are accompanied by direct financial subsidies or incentives and rebates for installing charging stations at the customer’s home.

2.4. Private mobility supply

The supply for private mobility is quite diversified, with the alternatives represented by the different powertrain configurations. These are listed below in order of increased electrification level.

Starting from conventional powertrains, equipped only with an ICE, micro/mild hybrid powertrains are the simplest step towards electrification, where one or more electric motors aim to support the engine in situations where its efficiency is low, and fuel consumption would increase. Then, pure hybrid powertrains, which have been existing in the market since 1997 (Toyota Prius). These fully integrated vehicles have a higher reserve of electrical energy; they can blend in more ways the electrical and thermal power sources than mild hybrids can do; usually they can drive the vehicle in full-electric for a few km at low power requests. Next, Plug-in Hybrid Electric powertrains add the opportunity to be recharged from the electricity grid via stations, and they usually provide full electric driving capabilities for about 50–100 km, plus hybrid scenarios both in parallel and series configurations. Complexity of such systems is the highest among all powertrain configurations so far. Finally, pure battery electric powertrains, which have autonomy ranges that span between a few hundred km to one thousand km for the new heavy-duty applications under development.

According to the choice of drivers in 2022 in Europe [29], gasoline powered vehicles are still the most popular, with 36 % of sales, followed by hybrid electric vehicles and diesels.

The applicability of a powertrain configuration depends on its interaction with the environment it is used into, since each of them has strengths and weaknesses from the point of view of the user. By looking at the extremes of the pool of alternatives, a conventional powertrain has the strengths to own the highest energy density among all configurations, and to rely on a widely spread infrastructure for refuelling - exponentially increasing its flexibility and use range. Its weaknesses are lack of electric support, leaving the engine alone into power generation and giving to the driver the entire responsibility to optimise efficiency by adjusting the driving style, and the intrinsic GHG emissions during use, that are the core element of the debate.

A battery electric powertrain, on the other hand, shows as its strengths a high energy efficiency that is spread over almost the whole speed range, and no GHG emissions during use. The weaknesses are its low range, due to a low power density and scarce recharging infrastructure.

From a system point of view, taking in consideration aspects that the end user does not perceive directly, electric vehicles require materials that are sometimes very rare on Earth, and there are implications from an environmental and social standpoint.

3. Methodology

As described in the introduction, the paper goal is to assess the opportunity to diversify the application of the different powertrain configurations according to the demand and the composition of the transport patterns in different areas, showing that - limiting the behaviour of every powertrain configuration in a specific pattern of use - the efficiency and emissions are drastically different.

To do so, this work required an initial dataset, which is the same used in [24] and was provided by a car manufacturer, including 221′738 trips, made by 1085 different car drivers over a year in some European countries (the majority in Italy, with a smaller amount in Germany, France, UK, and Spain). Hence, the developed algorithm was tested on a statistically significant number of entries, but smaller than the expected value of entries for a town or city. Furthermore, since the data was provided by a single manufacturer, the numerical results presented cannot be considered fully representative of the population as they only included the OEM models of the SUV-B segment. However, the dataset was considered sufficient to test the methodology and its scalability to larger numbers Fig. 4

The dataset was then carefully cleaned of any incomplete entries, replacing them with the average value where possible, or eliminating the entry completely if this compromised subsequent analysis. At this point, the features of the dataset were identified by statistical analysis. Parameters such as the distribution of travel times, idle times, peak and off-peak times were determined.

Clustering was then carried out using the k-means algorithm in order to obtain representative journeys of different groups of drivers with different needs. Using the journey dataset of n data points, clusters were created based on the evaluation of all the m numeric variables. To this end, variables in non-numerical format have been transformed and formatted as numbers in order to be able to increase the number of variables to be considered and consequently the accuracy of the result.

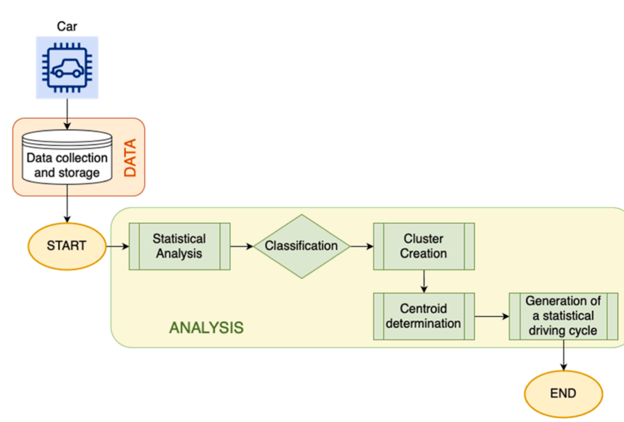

Fig. 4. Methodology followed in order to analyse the data and generate the driving cycle.

As the number of clusters increases, the variability (or differences) within each cluster decreases.

Given a dataset $X = \{x_1, x_2, \ldots, x_n\}$, where each x_i is a data point in R^m(i.e., an m-dimensional space), the K-means algorithm partitions the dataset into k clusters, minimizing the within-cluster variance. The objective is to minimize the following cost function:

$$\min_C \sum_{i=1}^{k} \sum_{x_j \in C_i} ||x_j - \mu_i||^2 \tag{1}$$

Where:

- k is the number of clusters.
- C_i represents the set of data points assigned to cluster i.
- μ_i is the centroid (mean) of cluster C_i.
- $||\boldsymbol{x_j} - \boldsymbol{\mu_i}||^2$ is the squared Euclidean distance between data point x_j and the centroid μ_i.

The ideal number of clusters k is selected by finding a balance between the number of clusters (which affects interpretability) and the reduction of variability within clusters (which improves the precision of grouping). This was achieved by minimizing the sum of squared Euclidean distances between each data point and its respective cluster centroid as in Eq. (1).

The process was repeated until convergence, ensuring that the resulting k cluster centroids accurately represented the underlying data structure in a both meaningful and accurate way. The centroid of each cluster represents the average values for each of the m numeric variables evaluated. These centroids are key points in the dataset, each with m-dimensions (one for each variable).

For each of these k points, i.e., trips identifiable as cluster means that were found with aggregate trip variables, the profiles of vehicle speed, angular engine speed and instantaneous fuel consumption over time were then analysed. This deepened the analysis down to punctual variables that constitute the core of the methodology. In fact, it was upon this data that the 'representative average' driving cycle was constructed, which was then necessary for a calculation of the WTW impact of the specific vehicle at that time and thus for sending the instantaneous environmental eco-label.

On the aggregated features of the entire dataset, trip composition percentages - urban, suburban, highway - were established. The speed profiles of the k centroids were then segmented based on speeds. Segments with speeds greater than *90* km/*h* were categorized as highway, less than or equal to *90* km/*h* as extra-urban and <*50* km/*h* as urban too. Segments belonging to each of the three categories were then averaged with each other, considering the specific distance and sequenced respecting the percentages on the average travel time derived from the dataset and to respect the average speed derived from the dataset.

The raw average cycle was finally post-processed again, smoothing by means of a moving average on a window of 1/150 cycle, in order to obtain accelerations compatible with the vehicle category under consideration.

At this point, the cycle is considered to be representative of the behaviour of the vehicles in the dataset. From the cycle, the average consumption per kilometre is obtained, given the mass of the vehicle, ignoring the energy contributions provided by any regenerative braking. By supplementing the powertrain information, it is finally possible to estimate the emissions in terms of tons of CO_2 equivalent.

4. Results

4.1. Statistically differentiated driving cycle

The trend of frequency of the trips over trip length is consistent with what has been found in the literature: frequency is higher for shorter trips, and it decreases hyperbolically with increasing distance (Fig. 5). It is reported for thoroughness that the trend is the same in all countries analysed and, thus, it is not influenced by the geographical region when remaining within Western Europe.

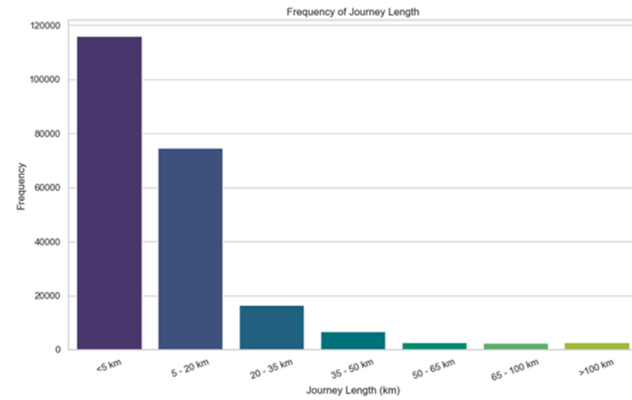

Fig. 5. Correlation between distance driven per trip and frequency of the trips.

The mean distance covered is 11.4 km with a standard deviation of 23.3 km. The median is 4.6 km, and the modes are 0.5 and 1.9 km. As far as travel times are concerned instead the average is 15.5′, the median is around 10′, and the mode is 2.5′. Even if on average the trips are short both in time and space, the majority of them can be classified as extra-urban, as it is possible to appreciate in Fig. 6. The classification depends on which category constitutes the highest percentage of each journey. Based on that, a label ("urban", "extra-urban" or "highway") is assigned to each journey.

The distribution in terms of frequency of trip compositions by % of km travelled is depicted in Fig. 7. It is evident that trips with 100 % of km driven in urban context occur frequently. Conversely, 100 % extra-urban trips are less common but still significant when selecting the optimal powertrain.

Moreover, the trends concerning the distribution of idle time reflect what is appreciated in the literature (Fig. 8). There is a higher frequency for short stops (under 40′) and then a downward trend as the number of minutes of idle time increases. It can be seen that there are local maxima in correspondence with stopovers between 8 and 13 h, which likely represent stops due to work activities or overnight parking.

Finally, it is interesting to note, when exploring the dataset, how many of the urban trips are followed by other urban trips. Two trips are considered non-consecutive if, although the next trip results to be mostly

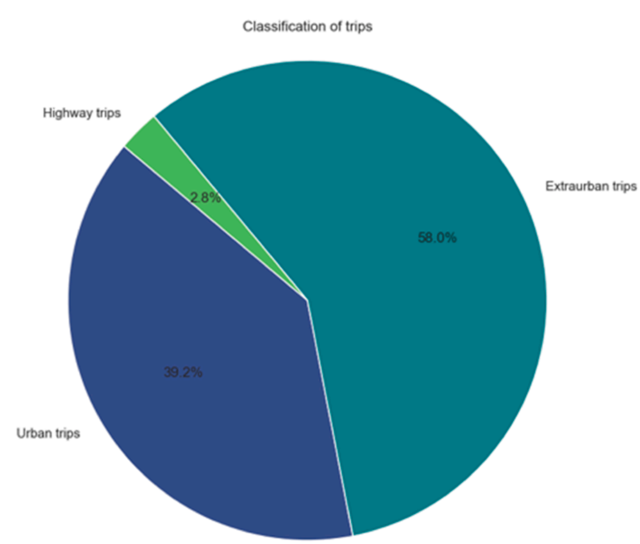

Fig. 6. Trip classification depending on the average speed. The percentage is on the total number of trips.

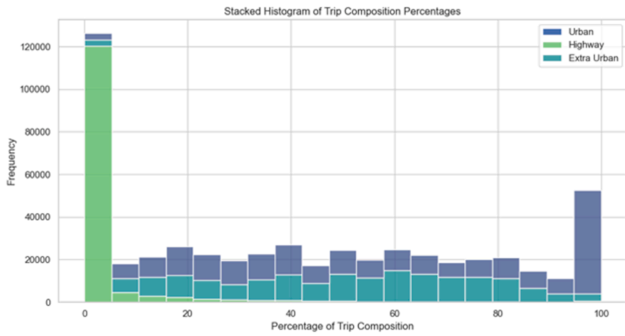

Fig. 7. Distribution of the frequency of the trip per trip composition.

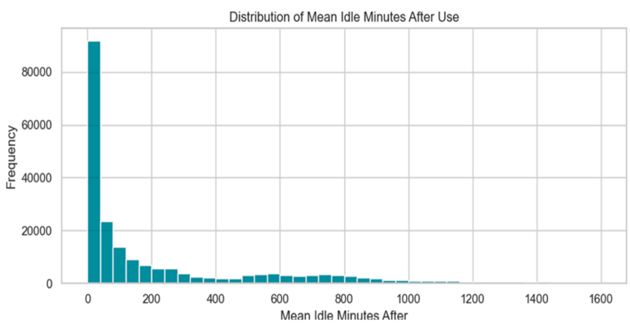

Fig. 8. Frequency of the mean duration of the idle after a single trip.

in urban area, the stop time between the two trips was sufficient to recharge the battery of an equivalent electric car of the amount of energy used during the first trip without considering regenerative braking. Fig. 9 shows that most trips are non-consecutive. Moreover, it is possible to appreciate from Fig. 10 the distribution of the trips per user that would not allow recharging the battery of the discharged amount with a 3 kW domestic power.

By clustering the data, a driving cycle reflecting actual driving habits can be derived. First, the average of the percentage of urban, extra-urban and highway driving was considered.

On the retrieved percentages, an average driving cycle was created from the prior clustering. The data-driven combined driving cycles has the following characteristics:

1). Timespan: 2600 s
2). Average speed: 41.1 km/h (with a std of 29.7 km/h)
3). Trip composition:

a) Urban: 57 %
b) Extra-urban: 39 %
c) Highway: 4 %

This driving cycle, shown in Fig. 11, was obtained by splitting the

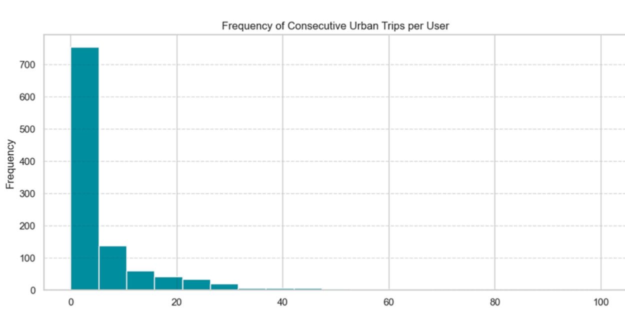

Fig. 9. Distribution of consecutive urban trips per user.

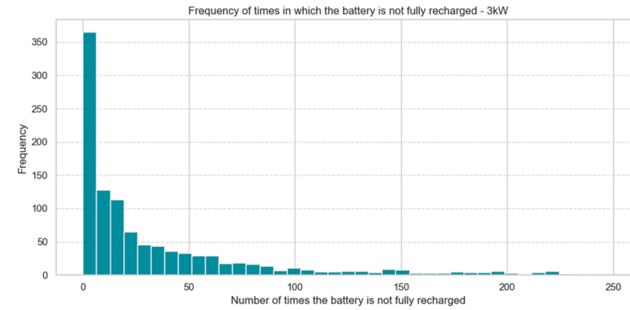

Fig. 10. Frequency of the trips that would not allow to fully recharge the battery after use.

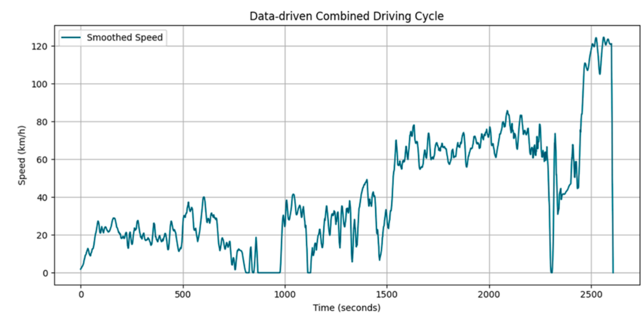

Fig. 11. Data-driven driving cycle.

sixteen driving cycles into urban, extra-urban and highway segments according to punctual speed. After performing this subdivision, the cycles were averaged. Next, accelerations were corrected using a moving average, obtaining acceptable values for B-SUV segment cars, yet more aggressive than the WLTP with a maximum of 2.7 m/s^2.

Over this data-driven combined driving cycle, engine revolutions are also tracked: they are higher in the extra-urban and highway part, although they never reach the rightmost part of the engine map. The average for the urban section is around 1281 $\pm$ 286 rpm, while it rises to 2310 $\pm$ 335 rpm in the remaining extra-urban and highway sections.

The results obtained are the foundation for the considerations put forward in the following paragraphs.

5. Discussion

Having outlined the analysis of the driving cycle and having collected existing literature on this subject besides market situation [30], it is possible to present the idea behind the paper, that is *to separate urban and non-urban scenarios* considering the acquired data and the shape of the statistically differentiated driving cycle, leveraging technologies currently under discussion in the EU committee. The two scenarios are described below.

5.1. Urban driving cycle

The first part of the cycle encompasses the urban segment, where tailpipe pollutant emissions must be the lowest.

A first notable factor is that, on average, the urban segment composes 57 % of the trips, and this is also due to the slightly but steadily increasing level of urbanisation: about 3 out of 4 people in Europe live within urban conglomerations [21]. Due to traffic and intersections, the travel speed pattern in cities is generally not uniform, with numerous decelerations and accelerations. This behaviour is well fit for the use of electric motors, given their high efficiency and quick response to speed gradients; ICEs would behave poorer instead: in fact, they would work at very low engine revolutions and loads, greatly increasing fuel consumption. In addition, electric motors can be used to recharge the battery during braking. Vehicles with electric powertrain achieve efficiencies during driving (TTW) of about 71 %, significantly better than those of an ICE powertrain which in these contexts have efficiencies ranging around 18–20 %.

However, the production and distribution of the electricity used to power the BEVs should also be considered. In fact, the TTW efficiency may convey the idea that the BEVs are unrivalled, but when referring to the WTW, the efficiency of the BEVs decreases. If the electrical energy is produced with fossil fuels, the resulting WTT efficiency is between 35 and 40 %, for a total over the WTW of 27 %. In fact, as seen in the section on mobility supply, in the short term, the marginal increase in electricity demand must be satisfied mostly by the combustion of gas, oil or coal.

Some considerations can be made at this point:

1). HEVs could use fuels with very low emissions from a WTW perspective. This is the case of HVOs with CO_2 captured from biomass during fuel production or e-gasoline and e-Diesel if produced with renewable energy sources with CO2 captured from air via Direct Air Capture [22].
2). BEVs should be made accountable of the emission intensity of the grid mix during recharging; in Europe on average this is around 255 g $CO_{2\ eq}$/km.
3). PHEVs would combine the two previous factors. Moreover, the Energy Management System algorithm could allow preferentially electric-only driving within the geofenced area.
4). Lastly, FCEVs should consider the hydrogen production process, given that the fuel cells need high quality and purity of the compressed gas and currently the percentage of green hydrogen is limited.

The statistically differentiated driving cycle has the scope to show that, depending on the context where the powertrain is used, its performances greatly differ. Together with the other aspects that were highlighted in the private mobility demand section, the driving cycle takes part to the set of variables that define the most suitable powertrain configuration per context.

A sensitive aspect to consider is the transition phase involving the coexistence of admitted and non-admitted vehicles and the alternatives to them; this issue is addressed hereafter.

5.2. Non-Urban: extra urban and highway driving cycle

The second part of the statistically differentiated driving cycle, on the other hand, is where emission limits are less stringent. It refers to suburban and highway areas, where the WTW efficiencies of ICEs and BEVs are not too different. In fact, at this stage the ICE works at higher loads and higher rpm, close to the engine's zone of maximum efficiency. Then by creating HEVs or PHEVs architectures that benefit from the high performance of the ICE at high loads and of the electric motor in transients, a wider range of peak efficiency can be exploited. Moreover, longer ranges of autonomy can be guaranteed without burdening the vehicle with additional weight.

Considering the aforementioned factors, as well as the lifecycle of a car, it might be more cost-effective for an average user, who spends about 44 % of the time out of the urban context, to own a PHEV or HEV equipped with batteries with capacity ranging from 8 to 15 kWh which offers an electric driving capability of up to 60 km, possibly 100 km in the next few years. This way, compared to a full transition to BEVs, it is possible to save on the share of emissions due to the extraction of raw materials - China's near-monopoly - and the production of the batteries. Furthermore, being able to make use of alternative fuels on ICEs, such as HVO, already available on the market, but also hydrogen or ammonia, brings the advantage of a stable powertrain production chain, which uses non-rare and less expensive raw materials.

In particular, the possibility of using the ICE to only recharge the battery should not be overlooked: it extends the vehicle autonomy by making the engine work only at points of maximum efficiency.

As already mentioned, managing the transition of such a manoeuvre is a delicate and important factor for it to be socially sustainable.

5.3. Technologies - eco label and geofencing

The driving cycle alone does not allow to reach the goal of discriminating propulsion mode per typology of trip, but it is a tool which enables the use of technologies in the quest for *zero carbon emissions in urban areas* and for boosting the efficiency of the conventional propulsion modes.

For instance, *geofencing* - which is also explicitly mentioned by EURO 7 regulation - can be used to inform the vehicle that it has entered specific areas where carbon-based tailpipe emissions are not allowed, and with a given limit on pollutant emissions; the vehicle would be, hence, prompted to switch to a carbon-neutral energy carrier. If no energy carrier on the vehicle is carbon-neutral, the driver would be advised to stop outside from the area or leave it as soon as possible to avoid incurring in a fine.

First of all, the temporal and spatial extent of the geofenced zone should be considered: indeed, emission levels could increase around the protected area, as drivers who do not want to adapt or cannot afford new clean vehicles may be tempted to increase parasitic traffic outside the urban protected zone. In addition, if the solution is active only at predefined times, increased traffic before and after the restricted hours could be expected. The proposed solution, keeping a low level of pollutant emissions in the personal transportation chain, advocates the activation of a *permanent geofenced zone* that is as wide as possible.

To the problem of discriminating vehicles admission, a possible solution is similar to what have been already experimented in Italy for vehicles not meeting the latest EURO 5 and 6 standards, called MOVE-IN [24], or *MOnitoraggio dei VEicoli INquinanti* – i.e. monitoring of polluting vehicles. With this strategy it is possible to get the installation of a black box with a budget of kilometres dependent on the standard which the vehicle meets, upon payment of a nearly negligible sum. In this way, it is possible to minimize the circulation of polluting vehicles, without forcing the private citizen to change the car neglecting his/her purchasing power, thanks to easy technological retrofitting.

However, this solution can also be developed at a global scale. The proposed driving cycle would be used to assess the vehicle detailed emissions in the urban and non-urban contexts. This information would be added to a value of carbon-intensity and environmental score resulting from the Life Cycle Assessment applied on the vehicle. With all these data in hand, a *label* for the vehicle could be created, that would be affected also by the type of energy source that would be used (e.g., electricity generated from sustainable sources or with fossil fuels). The computed label would provide an access tool to restricted areas provided that specific requirements are met. This way, a vehicle that is produced and transported following sustainability guidelines would be preferred to a vehicle that does not follow such practices.

The impacts of the presented approach would be many. For instance, not all drivers would have to switch to an electric vehicle; in fact, those who live outside from cities and travel in non-urban contexts would have the opportunity to stick to conventional powertrains and just change the fuel type used by the engine, maybe preferring an e-fuel or an HVO, leading to a further reduction in global CO_2 emissions. In case of an urban trip, public transport could be considered. This would require for a change into ~~their~~ travel habits, which goes beyond the goal of this paper, but this framework would provide a push towards a modal shift and an integrated approach to mobility.

Aside from the customers, beneficial impacts would be present also for the car industry, that could still rely on the know-how of ICEs, proving that they are still well fit for road transport, thanks to the technological advancements, and the energy sector because there would not be the necessity to provide enough electrical power to supply the entire vehicle market as if it all shifted to electric.

6. Conclusions

Based on real driving data, a statistical analysis, clustering and the creation of a data-driven driving cycle were conducted, to show how the behaviour of the different powertrain changes depending on the driving use case.

It has been highlighted how the efficiency of an ICE is varying (48 % down to 16–18 %) according to the driving speed and the irregularity of driving.

Electric vehicles are a better fit in the urban context, characterised by shorter trips and consecutive sequences of accelerations and decelerations.

On the other side, in non-urban contexts, the wide efficiency of the electric powertrains is not used, since speeds tend to be less variable with less interruptions. Moreover, since trips are usually long, the issues of the range and where to recharge the battery arise.

In this case, a conventional or a hybrid powertrain is the most appropriate solution, better if equipped with an energy carrier that fosters de-fossilisation, like e- and biofuels.

This approach would be in line with a point of observation that considers the entire life cycle of the vehicle, including the one related to the well-to-tank of the energy carrier.

This way, all impacts are considered, also the ones that are not related to the use of the vehicle.

Mobility habits are evolving over time, and the demand for private transportation is still a backbone of daily mobility.

Hence, this work aimed to show how each powertrain and energy carrier better fit to different driving use cases, highlighting that the road to de-fossilisation and the analysis of the environmental impact is made of multiple solutions applied to the proper situation.

CRediT authorship contribution statement

Simona Gurrì: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Flavio Cappelli:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Bruno Dalla Chiara:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition.

Declaration of competing interest

I declare that there are no conflicts of interest.

Acknowledgements

This research was supported by a PRIN 2022 project, a research programme funded by the Italian Ministry of University and Research, as part of a project called 'URGET VADEMECUM 2030–50′ (URban de-pollution and de-carbonisation from emissions GEnerated by Transport systems: eVAluation of DEdicated Methodologies, technologies and EConomic thresholds for an unprecedented Mobility at 2030–50).

Data availability

The data that has been used is confidential.

References

[1] Statista.com, "Distribution of carbon dioxide emissions worldwide in 2023, by sector," [Online]. Available: https://www.statista.com/statistics/1129656/global-share-of-co2-emissions-from-fossil-fuel-and-cement/.

[2] European Parliament, "Regulation (EU) 2019/631," [Online]. Available: https://eur-lex.europa.eu/eli/reg/2019/631/oj/eng.

[3] European Parliament, "Euro 7 standards: new rules for vehicle emissions," [Online]. Available: https://single-market-economy.ec.europa.eu/document/download/3c4a2b43-3453-4898-80bf-109ef0828eb2_en.

[4] European Parliament, "Directive 2014/94/EU," [Online]. Available: https://eur-lex.europa.eu/eli/dir/2014/94/oj/eng.

[5] European Parliament, "Directive 2008/50/EC," [Online]. Available: https://eur-lex.europa.eu/eli/dir/2008/50/oj/eng.

[6] European Parliament, "Directive (EU) 2024/2881," [Online]. Available: https://eur-lex.europa.eu/eli/dir/2024/2881/oj/eng.

[7] European Parliament, "Directive 2009/28/EC - Renewable Energy Directive," [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:32009L0028.

[8] European Parliament, "Directive (EU) 2018/2001," [Online]. Available: https://eur-lex.europa.eu/eli/dir/2018/2001/oj/eng.

[9] European Parliament, "Directive 2009/30/EC," [Online]. Available: https://eur-lex.europa.eu/eli/dir/2009/30/oj/eng.

[10] European Parliament, "Regulation (EU) 2017/1151," [Online]. Available: https://eur-lex.europa.eu/eli/reg/2017/1151/oj/eng.

[11] European Parliament, "Regulation (EU) 2016/427," [Online]. Available: https://eur-lex.europa.eu/eli/reg/2016/427/oj/eng.

[12] E.E. Agency, "Passenger transport activity," [Online]. Available: https://www.eea.europa.eu/en/analysis/publications/sustainability-of-europes-mobility-systems/passenger-transport-activity?activeTab=bb19ae58-42be-4df9-97da-2e891e1ebcdd.

[13] European Parliament, "Regulation (EU) 2024/1257 - euro 7," [Online]. Available: https://eur-lex.europa.eu/eli/reg/2024/1257/oj/eng.

[14] S. Kosai, M. Nakanishi, E. Yamasue, Vehicle energy efficiency evaluation from well-to-wheel lifecycle perspective, Transport. Res. Part D: Transp. Environ. 65 (2018) 355–367.

[15] European Environment Agency, "Greenhouse gas emission intensity of electricity generation," [Online]. Available: https://www.eea.europa.eu/en/analysis/maps-and-charts/co2-emission-intensity-15?activeTab=6fbd444d-c422-4a78-8492-fd496bd61b7a.

[16] M. Romare, L. Dahllöf, The Life Cycle Energy Consumption and Greenhouse Gas Emission from Lithium-Ion Batteries – A Study With Focus on Current Technology and Batteries for Light-Duty Vehicles, IVL Swedish Environmental Reseach Institute, 2017.

[17] ICCT, "CO2 emission standards for new passenger cars and vans in the European Union," 2023. [Online]. Available: https://theicct.org/wp-content/uploads/2023/05/eu-co2-standards-cars-vans-may23.pdf.

[18] OPEC, Distribution of oil demand in the OECD in 2022, by sector, Statista (2023) [Online]. Available, https://www.statista.com/statistics/307194/top-oil-consuming-sectors-worldwide.

[19] Wolkswagen, "CO2" [Online]. Available: https://www.volkswagen.be/fr/co2.html.

[20] D. Jones, S. Brown, P. Czyzak, European Electricity Review 2023, Ember Energy, 2023.

[21] R. Smit, D.W. Kennedy, Greenhouse gas emissions performance of electric and fossil-fueled passenger vehicles with uncertainty estimates using a probabilistic life- cycle assessment, Sustainability 14 (6) (2022) 3444.

[22] A. Comi, U. Crisalli, S. Sportiello, Forecasting the vehicle energy potential to support the needs of electricity grid: a floating car data-based methodology, Front. Fut. Transport., Sec. Transport. Syst. Model. 5 (2024).

[23] B. Dalla Chiara, F. Deflorio, M. Pellicelli, L. Castello, M. Eid, Perspectives on electrification for the automotive sector: a critical review of average daily distances by light-duty vehicles, required range, and economic outcomes, Sustainability 11 (20) (2019) 5784.

[24] B. Dalla Chiara, F. Deflorio, M. Eid, Analysis of real driving data to explore travelling needs in relation to hybrid–electric vehicle solutions, Transp. Policy (Oxf) 80 (2019) 97–116.

[25] G. Brancaccio, F.P. Deflorio, Extracting travel patterns from floating car data to identify electric mobility needs: a case study in a metropolitan area, Int. J. Sustain. Transport. 17 (2) (2023) 181–197, 02-01.

[26] European Court of Auditors, "Infrastructure for charging electric vehicles: more charging stations but uneven deployment makes travel across the EU complicated," *EU Special Report,* 2021.

[27] J. Zhang, X. Gong, From clicks to change: the role of internet use in fostering environmental sustainability awareness, J. Environ. Manage. 348 (2023) 119275.

[28] F.M.M. Cirianni, G. Leonardi, Analysis of transport modes In the urban environment: an application for A sustainable mobility system, WIT Trans. Ecol. Environ. 93 (9) (2006).

[29] ACEA, "Fuel types of new cars: battery electric 12.1 %, hybrid 22.6 % and petrol 36.4 % market share full-year 2022," 1 February 2023. [Online]. Available: https://www.acea.auto/fuel-pc/fuel-types-of-new-cars-battery-electric-12-1-hybrid-22-6-and-petrol-36-4-market-share-full-year-2022/. [Accessed 2024].

[30] M. Marabete, B. Dalla Chiara, C. Maino, E. Spessa, Electrified road transport through plug-in hybrid powertrains: compliance by simulation of CO2 specific emission targets with real driving cycles, Transport. Res. Interdisciplin. Perspect. (2022).