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Freight vehicles powertrain's hybridization: assessment of their range of competitiveness through a technical and economic analysis based on user requirements and available technologies

Relatori

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ABSTRACT

This M.Sc. thesis provides an overview on the currently available alternative fuel technologies and solutions for commercial and industrial vehicles, besides the policies to support their adoption. The information and data here shown, other than the resulting considerations drawn, are obtained through an extensive literature review of the technical and economical researches, moreover from the data on real cases. Consequently, the specific case of urban light-commercial and medium-duty vehicles is analyzed in economic terms. This example confirms how there are already applications for which battery electric vehicles already achieved the total cost of ownership parity with diesel commercial vehicles. In parallel, a technical analysis has been conducted to find the limitations of pure battery vehicles in urban and suburban areas, regarding mass, range and performance limits. Via simulation tools and real life gathered data, these deficiencies are highlighted and potential solutions are proposed.

Questa tesi fornisce una panoramica delle tecnologie di propulsione alternative e in particolari le applicazioni su veicoli commerciali e industriali, oltre alle normative che ne incentivano l'adozione. I dati e le informazioni qui forniti, in aggiunta alle conclusioni da essi derivate, sono ottenuti attraverso un'estesa ricerca della letteratura economica e tecnica su questo tema, oltre a dati raccolti sul campo. Successivamente, il caso specifico dei veicoli commerciali leggeri e medi ad uso urbano viene analizzato economicamente. Questo esempio conferma come esistano già delle applicazioni in campo pratico per le quali veicoli puramente elettrici hanno già raggiunto lo stesso costo totale di gestione di un veicolo diesel. In parallelo, viene svolta un'analisi tecnica per identificare eventuali limiti the veicoli puramente elettrici ad uso urbano ed interurbano, in termini di massa, missione, autonomia e performance. Attraverso strumenti di simulazione e dati raccolti sul campo, tali deficienze vengono evidenziate e potenziali soluzioni sono fornite.

TABLE OF CONTENTS

1 INTRODUCTION

In recent years, the growing concern for the environment brought many national and international initiatives to tackle the rising and worsening threat of global warming. Although the concreteness of such measures can be argued, examples such as COP 21 and national emission's regulations have not only emphasized the urgent need for tangible actions but have spread such concern on all spheres of our society.

As elicited by the World Economic Forum in their 2019 Report (Exhibit 1), environmental issues are the most dangerous and concrete for the next generations. Out of all the investigated risks, the 3 most probable to happen are all environmental (circled in the graph and then ranked below it), being those, at the same time, within the 4 most impactful ones. In particular, the interest of this thesis will be directly related with the risk of "*Failure of climate-change mitigation and adaptation*".

The importance of freight vehicles' emissions regulations became evident in early 2000s, when road freight transport's oil demand outpaced all other sectors. The study of the International Energy Agency (2017) estimated that those vehicles were responsible for 80% of the global net increase in diesel demand from 2000 onwards. On the contrary, oil use of passenger cars has flattened or even decline in few industrialised countries, worsening this situation with road freight vehicles making up half of global diesel demand. As a result, 35% of transport-related CO_2 emissions are imputable to road freight and 7% of total energy-related CO_2 emissions, according to IEA (2017).

As claimed by the European Union's 2030 climate and energy framework, a reduction of GHG emissions 30% below the 2005 baseline will be needed, before 2030, in the sectors of transport, building, agriculture and non-ETS (emissions trading system) in general emissions. This framework was adopted by EU leaders in October 2014 and it is part of the set of measures, in terms of 2020-30-50 binding targets, to implement the global action plan of the Paris Agreement. This settlement was signed by 195 at the COP21 meeting and constitutes the first-ever universal legally binding global climate deal (Paris Agreement, 2016). This meeting pursues efforts to limit global warming to 1.5 °C and avoid dangerous climate changes predicted for the scenario of a 2 °C increase (e.g. sea level increase). While EU has set progressively restrictive emission's limits on car and vans (respectively 95 and 147 gCO_2/km before 2021), the regulation for HDVs (Heavy Duty Vehicles) arrived very late, lacking behind many other countries such as China and Japan. As will be shown later, many international countries look to European Union as an example for legislative measures and policies, meaning that the lack of a specific emission's regulation for commercial vehicles would have had repercussions on a global scale unless immediate actions are taken. It is expected that, after the enactment of the aforementioned HDV regulation by the EU, other countries will adopt it, since a joint effort is needed in order to effectively reach the targets set by the Paris agreement.

The urgency and concern for such matters, brought to many studies and researches in this field. The findings of Muncrief and Rodríguez (2017) show that we would be able to reduce fuel consumption of HDVs, from today's level, by 30% to 40% using existing and conventional technologies aimed at increasing engine's (mainly diesel) efficiency and reducing vehicle's road-load power demand. An even greater reduction and, in some cases, potentially going towards the 100% goal could be achieved with the introduction of alternative fuels. This target is still utopian due to the fact that the analysis cannot be limited to the vehicle itself, instead it should consider the whole chain of production and use of the specific fuel, (being it conventional, alternative or electricity) through the WTT (Well to Tank) index. This concept is debated by many professionals and policy makers concerning the fact that it would be much more impactful to regulate the whole lifecycle emissions.

Currently in use in many countries, alternative fuels such as LNG (Liquefied Natural Gas) and CNG (Compressed Natural Gas), both available as mono-fuel and flex configurations, have been gaining consensus in many regions of the world. Similar trend has been experienced by Biofuels: initially introduced in Brazil, the industrial production of such propellant has spread around the globe being it nontoxic, biodegradable and its combustion produces less air pollutants. Especially for the last argument, reports and studies on the efficiency of such fuels are contradictory, since the fuel is not the only contributor to the overall yield of an engine; other factors may include the injector type and pressure and the combustion conditions. Overall, there are evidences that the aforementioned solutions would be able to achieve similar, and in some particular cases even better (when blended with conventional diesels), performances compared to conventional internal combustion engines (ICEs). Still, a big barrier to their widespread adoption is the extensive use of land for the production of Biofuels, particularly considering the forecasts of increasing demand for land for food supply. To face such threat, the European Union has introduced a limitation of the contribution of conventional biofuels for 2020 and the obligation to establish national target for the development and deployment of advanced biofuels (Directive (EU) 2015/1513). This limitation makes evident the fact that probably there is not a definitive solution. A rather more realistic scenario is a *blend* of different fuels and transportation means according to each specific advantage and limitation in relation to the personal and business needs.

As introduced in previous paragraphs, a third (apart of producers and customers) important party playing a key role it's constituted by local and national authorities. Governments are publicly pursuing efforts by signing international acts, as the Paris agreement, and promulgating national legislations and policies to ensure their compliance to the targets set. They are also responsible for bearing the costs related to incentives and promoting campaigns for the adoption of alternative fuel vehicles. Especially in the sector of passenger vehicles, almost every developed country has introduced such policies, while as stated before, this is not the case of commercial vehicles. Even more crucial in this dissertation is the importance of governments in the construction of an appropriate infrastructure to sustain and boost the adoption of sustainable transport solutions. While for electric passenger cars and LDVs (Light Duty Vehicles) the costs can be shared, in different proportions, with private organisations, such as car sharing and mobility solutions, or delivery services companies, for electric HDV and hydrogen vehicles the investments required are of a much different magnitude. As will be highlighted in chapter 3, there have been many experiments, particularly in Sweden, on in-motion charging methods, a way of charging vehicle's batteries without the need to stop at a charging station, through inductive infrastructures under the road surface or catenary conduction, through wires hanged at few meters over the road path. Both solutions have pros and cons, particularly the inductive method requires bigger investments and longer timeframes of implementation, while the conductive charging infrastructure requires bigger, and not so straightforward, modifications to the vehicles as well. These reasons may justify why big investments for such technologies has been done exclusively by or for public transportation companies, apart from private companies' experiments such as Scania in Sweden. The investment needed to extend the vehicles range would be prohibitive for such companies, due to the bigger size of their fleets. While the reducing cost of batteries will be able to incentivize even more the use of EVs for private owners, it would allow, combined with charging stations at the bus stops, to reduce the BEP (Break-Even Point) for public transportation companies.

Simultaneously, local communities, particularly metropoles and federal states such as California, have been investing even more time and resources compared to their respective states and governments. Hall, Cui and Lutsey (2018) have performed a study on 25 metropolitan areas that have experienced the highest cumulative electric vehicle sales, called the EV Capitals[1]. According to the research, in 2017 the volume of sales reached 1.4 million electric vehicles, representing 44% of the global EV sales, even though such cities only account for 12% of global passenger vehicle sales. Pioneer of this group is Norway, which is investing heavily on the electric transition, also due to its energetic peculiarity, such as the high capacity and low-cost renewable potential. This allowed Bergen and Oslo to reach respectively 50% and 40% EV sales' share (the highest in the group), while the worldwide vehicles sales' share of EV was 1%. Albeit passenger vehicles sales are mainly made by private owners, EVs fleets include government cars, car-sharing, autonomous vehicles researches, taxis and buses between others. For example, Shenzhen has been the first and largest city to fully transition its fleet of buses to electric. Another key statistic concerns the investments in charging stations, that in fact are much more related to the specific local authorities. According to the aforementioned research, all the 10 cities with the lowest number of EVs per charging point are Chinese, except for Paris and Amsterdam. The excellence achieved by these cities is the result of a careful implementation of tailored policies at multiple levels, providing policy templates for other cities at earlier stages of the transition to electric mobility.

These are just few of the disruptive trends that are reshaping the transport industry, together with 3D printing (that will reduce the need of transporting goods by producing them locally), self-driving vehicles and many other. There have been many experiments of autonomous driving trucks, such as those of Otto & Budweiser (October 2016), DB Schenker (November 2018) and Tesla (still not in production), although the biggest investments were made in the field of electric HDVs and LDVs. There are many international publications on these topics, particularly technical studies on the different technologies available, in production and development. Contrariwise, a lack of business and economical papers, analysing the requirements for organisations, both in terms of business' needs and investments, seems to be missing. This thesis aims at gathering and illustrating the different legislations in force and

[1] Beijing, Changsha, Chongqing, Guangzhou, Hangzhou, Qingdao, Shanghai, Shenzhen, Tianjin, Wuhan, and Zhengzhou, China; London, England; Paris, France; Tokyo and Kyoto, Japan; Amsterdam, Netherlands; Bergen and Oslo, Norway; Stockholm, Sweden; and Los Angeles, New York, San Diego, San Francisco, San Jose, and Seattle, United States.

technologies available, both in terms of business' needs (according to the specific vehicle category) and costs of implementation. Technologies will vary depending on the vehicle weight category, due to different business requirements. Evidently, the only category for which BEV (Battery Electric Vehicle) is feasible and economically convenient is the one of Light Commercial Vehicles (LCVs), justifying why international logistics and delivery companies are heavily investing on such solutions. The research will be conducted using the available data and information on technical and economic databases, specialised magazines articles and with the help of professionals in the automotive field. In particular, the Iveco engineers will help framing the research's boundaries and simulating a BEV application based on the data gathered in a real life application of a diesel van. The thesis sets herself the goal of answering to the following research questions:

- Identify what would be the costs for the final customer to invest in BEV (Battery Electric Vehicles) for an urban application, in which electric vehicles do not have problems in meeting the business needs. The thesis will take into account both the vehicle price increase (at the moment there's no battery that can compete, in terms of price, with diesel) and the available governmental incentives (tax reductions during the life of the vehicle and buying incentives from the state). It will be estimated whether it is convenient to shift to battery electric vehicles.
- Secondly, it will be assessed, considering the current state of the art technology, whether electric vehicles are a viable solution also for more demanding commercial applications. By removing most of the ideal conditions for BEVs that are typically encountered in urban areas, it will be assessed through a software simulation tool if the electric van is still able to complete daily tasks without the need of charging on-the-go. A qualitative sensitivity analysis will also be performed to understand if variations of the normal routine can also be covered.

2 THE LEGAL FRAMEWORK

The first regulations on vehicles' emissions date back to the 60s, when first researches and studies on urban smog and their effect on health. California pioneered the researches on possible solutions to tackle such problem and inspired other countries to follow their path. In 1956, based on the results of the Californian studies, the German Parliament asked the Association of German Engineers to develop general guidelines for a reduction in air pollution, including vehicle exhaust emissions (Glatz, 1987). In the same period the French government took a similar decision and, thanks to their joint work, in 1982 the European Commission (EC) introduced the first vehicle emission limits. By 1982 the emissions levels of all controlled emitting sources were just 50% of the original 1970 levels (A. Smith, H. Davies, 1996). Three years before, a similar legislation was introduced in the US, the Clean Air Act, setting emission levels at 30-40% of the estimated uncontrolled levels of 1967 and established the Environmental Protection Agency (EPA) to administer and enforce the limits. Thanks to the Californian research on the effects of exhaust emissions on human health, they were also the first to introduce restriction on the emissions of NOx in 1973.

As a consequence, in the successive years many other countries followed the lead of US and the EC. A global and common commitment to tackle the air pollution started to take shape and Japan, staring from the late 80s, acting as the guide of such group together with California. The latter one constantly introduced stricter regulations than those of EPA and "served" as an innovation hub to a huge number of environment and green start-ups, as Tesla in 2001. Japan instead incentivized investments in technology by setting the strictest emission control requirements for vehicles in Asia and among the strictest in the world. They have been one of the firsts to apply fiscal incentives to reward vehicle fuel efficiency and in 2005 Japan adopted the world's first fuel-economy regulations for heavy-duty vehicles (ICCT). These policies drove the Japanese car manufacturers to become the leaders in the R&D of advanced drivetrains for passenger vehicles, such as Toyota for hybrid engines and Nissan for full electric vehicles (BEVs) among others.

Even though the aforementioned regulations, and those that followed, created a binding enforcement for both manufacturers and final users (that needed to buy new cars to compel with the limits), the gas emissions of the transportation sector haven't reduced. The study of the

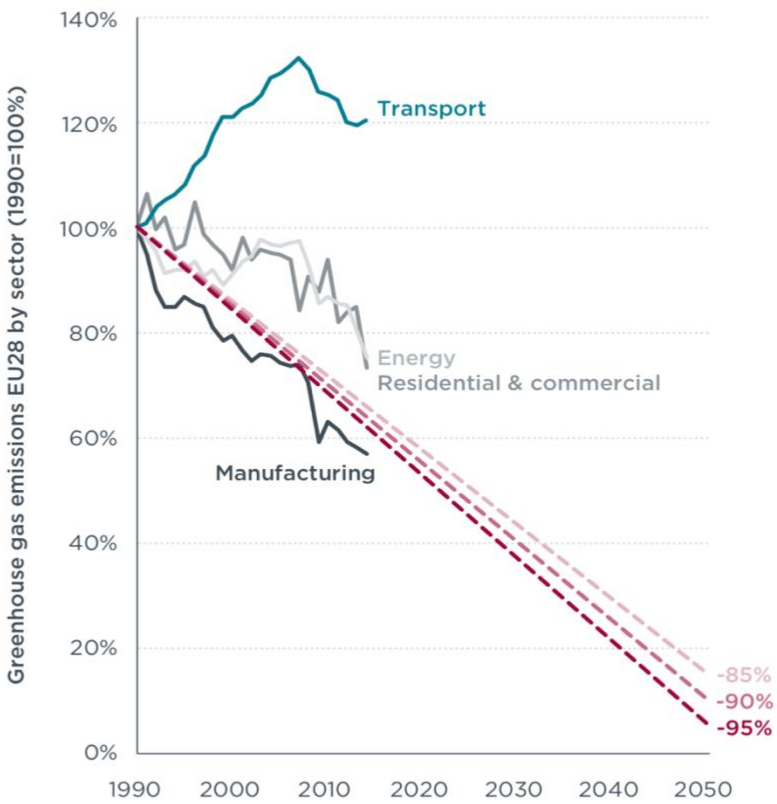


Fig. 1 Green-house gas emissions in the European Union by sector (source: ICCT, 2018)

International Council of Clean Transportation (Delgado & Rodríguez, 2018) highlights how all concerned sectors experienced a decrease of the corresponding greenhouse gas emissions compared to 1990 levels, following the targets set by the European Union, except for transportation. In the period from 2012 to 2018 the electric car sales grew by 61% (Mehta et al., 2019), passing for the first time the 2 million threshold, thanks to a growth peak of 75% in the last year. The IEA (2018) forecasted that the global sales of PEV (Plug-in EVs) and PHEV (Plug-in hybrid EVs) will reach 25 million in 2025, boosted by the increased effect of incentives and tax reductions together with the huge investments made by almost all car manufacturers. Albeit the overall demand for electric vehicles substantially increased in recent years, the EV sales correspond to a very small fraction of the global vehicles sales, around 2% in 2018 according to Hall, Cui and Lutsey (2018). For such reason, despite of the growing share of EVs, the scale effect of the increased use of road transportation pushes up the GHG emissions as from figure 1. There are potentially two factors contributing to this “dilution” effect: more indulgent regulations for commercial vehicles when compared to passenger ones and the lack of utilisation of a common efficiency index and evaluation method. The former stresses the urgency for a stricter and coordinated emission’s policy framework specific for the commercial vehicles segment. As can be seen in figure 2, the research of the European Automobile

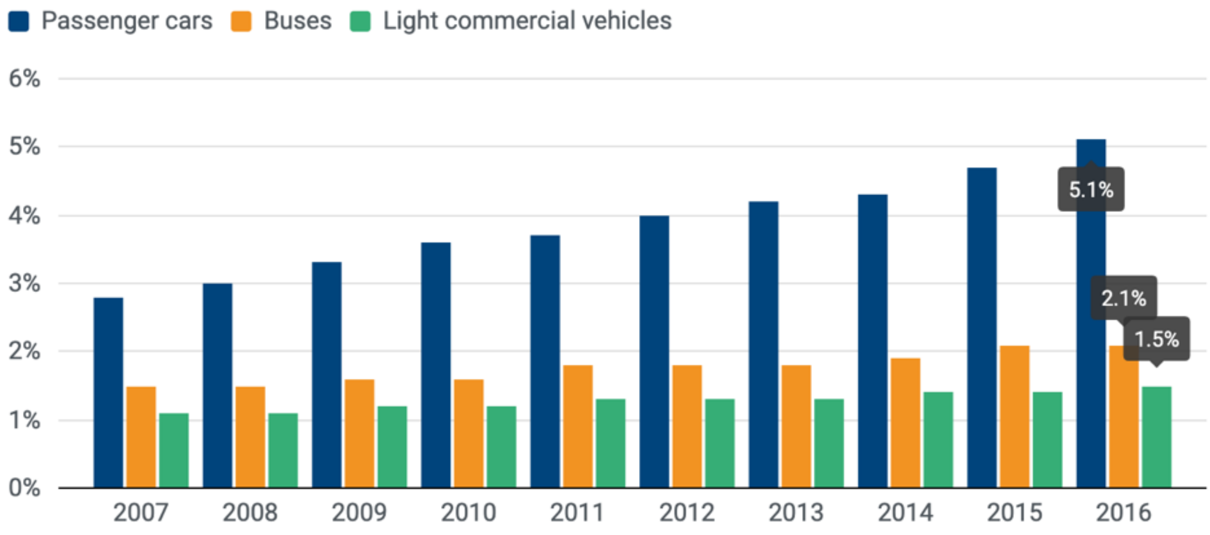


Fig. 2 Share of alternative fuel vehicles per vehicle segment (source: ACEA, 2016)

Manufacturers Association shows the effect of using different approaches in the emission's regulation on different vehicle segments. While electric passenger cars' adoption has been incentivised by stricter regulation and electric buses diffusion is encouraged by the transition toward sustainable public transportation of certain cities, LDVs conversion to electric powertrain is still slow and concentrated in certain regions of the globe. Concerning the lack of a common evaluation index, a theoretical parameter has been gaining importance in recent years, that is the WTW. It can be defined as the integration of all the processes required to produce and distribute fuel (starting from its primary energy source) and to use it in a vehicle and it is expressed by the following formula (Dalla Chiara & Pellicelli, 2016):

$$WTW\left[\frac{MJ_t}{km}\right] = WTT\left[\frac{MJ_t}{MJ_f}\right] \times TTW\left[\frac{MJ_f}{km}\right]$$

The Well-To-Wheel consists of the combination of two more specific sub-indexes:

- WTT (Well-To-Tank): concerning all the emissions related with the extraction of the fuel or the production of electricity, the so-called upstream emissions. The importance of this parameter is related to the fact that even PEVs could be polluting due to the resource used to produce the electricity that is consumed by the electric engine. By ensuring that this component of the index is high as well, the overall effect on the GHG emissions is doubled, thanks to an improvement in the energy sector as well. Even though this argument is out of the scope of this research, it shows how broad are the effects of the transition towards sustainable mobility.
- TTW (Tank-To-Wheel): takes into account the tailpipe emissions, the CO_2 emissions that occur during the combustion of the fuel and are affected by the performance and

efficiency of all the vehicle parts, rather than just focusing on the engine efficiency. The fuel consumption is affected by all energy losses of the vehicle, from the rolling resistance of the tires up to its aerodynamic drag. By improving this factor, the vehicle will reduce its overall emissions and also the consumption of fuel (being it fossil or alternative), resulting in a better utilisation of resources and lower cost for the owner.

Finally, an important discrimination factor is the evaluation method, or model, used to measure the efficiency of the vehicle. As will be seen in the next session, different countries adopt not only different regulations and limits on emission, but also the criteria and method used to measure them changes accordingly. Due to this, HDVs and LDVs manufacturers will have to adapt their vehicles' performance according to the target market's regulation rather than the local one. This can be a real challenge for European manufacturers (such as Scania), which are producing commercial vehicles according to the European legislation and could suddenly not be able to sell their product to the American market, where for example Scania and Daimler are market leaders with 46% of the market share combined. The reduction of the competitiveness deriving from the introduction of new legislations is something that has already shown its effects in the passenger cars industry. An example is provided by the case of Maserati trying to ship vehicles to China after the introduction of more stringent CO_2 emission standards. Due to a lack of preparation of Maserati on the target market legal framework, hundreds of cars had to wait in the port until a way of controlling the emissions electronically was found. This is just an example to highlight the need of coordinating the different worldwide standards also for the safeguard of manufacturers. On the other side, the latter need to invest more heavily on R&D to anticipate future market needs and emissions regulations.

2.1 <u>Commercial vehicles' classification</u>

In view of the fact that emission standards vary according to the truck weight class, it seemed reasonable to first provide an overview of the different classifications in force around the globe. For simplicity, along the next chapter a simplified classification criterion will be used, consisting of only 3 macro-categories of commercial vehicles. This framework is the one used by the International Energy Agency (2017) and is consistent for the use of this paper, particularly in the definition of LDVs and MDVs (Medium Duty Vehicles), that are the real scope of the analysis. The 3 macro-categories are defined as follows:

- Heavy-Freight Trucks (HFTs) or Heavy-Duty Vehicles (HDVs) are commercial vehicles with a gross vehicle weight (GVW) greater than 15 tons (t). They typically serve long-haul delivery of goods, have from two to four or more axles and a power rating of between 200 and 600 kW. Even though they constitute a smaller market compared to LDVs (in terms of number of vehicle), they are an important category in terms of emissions since they are operated essentially year-round, often covering more than 100 000 kilometres (km) per year. HFTs account for the majority (about 70%) of road freight activity (distance travelled) and about 50% of truck energy use. While heavy-duty trucks consume much more fuel on average per kilometre driven than smaller trucks, this does not necessarily mean that they represent a less efficient mode of freight transport. In fact, in terms of useful service (i.e. per tonne-kilometre), HFTs are the most efficient at transporting goods.
- Medium-Freight Trucks (MFTs) or Medium-Duty Vehicles (MDVs) are commercial vehicles with a GVW from 3.5 t to 15 tons. They include small lorries, rigid trucks and tractor-trailers as well as large vans. They tend to perform regional operations but also include public and commercial service vehicles, such as garbage trucks or fire- fighting trucks. In countries with a less-developed highway network infrastructure, the function of some MFTs mimics that of HFTs: they are used in long-haul operations and for transporting goods from central distribution hubs (warehouses and ports) to their final destinations, such as retail firms, or for transporting bulk building materials and resources.
- Light Commercial Vehicles (LCVs) are pickups, vans and small trucks with a GVW of less than 3.5 t. LCVs are one of two classes of light-duty vehicles (the other being passenger light-duty vehicles) and are used for the transportation of goods. For simplicity, in the paper the notation LDVs will be used as synonym of LCVs, although it must be kept in mind that, theoretically, the broader category of LDVs includes both LCVs and passenger vehicles. In general, the LCV fleet consists of vans, chassis cab-style vehicles, small open lorries and pickup trucks. They are used for a variety of tasks, including small-scale 'last-mile' deliveries, such as a postal or commercial delivery services, and for transporting industrial goods and building materials to and from work sites. In fact, the most interesting applications and the ones that are being tested in recent

years, are LCVs for urban delivery services and short-distance logistics (additionally to applications for public transportation).

Due to a series of innovations in the products and goods industries, such as 3D printing, shorter supply chains thanks to advancements in logistics and application of predicting models to implement Just-In-Time (JIT) production models, experts believe that MDVs and, in a certain part, also HDVs will disappear in the years to come. This is why the most promising sector for the application of alternative fuelled engines in the one of LDVs, although this argument will be analysed more in depth in the next chapters.

Classification schemes vary from country to country, according to the local legislation, and are in general much more detailed than the simplified version proposed above. An overview of the different schemes of the key legislating countries (many others such as Canada and Brazil follow these directives) is provided in figure 3 in terms of gross vehicle weight.

United States		European Union				China		Japan			
Vehicle Category	Weight (t)**	Vehicle Category	Weight (t)*	Trailers & semitrailers	Weight (t)	Trucks Weight (t)	Tractors Weight (t)	Trucks Category	Weight (t)	Tractors Category	Weight (t)
		N1	< 3.5								
2b	3.86 - 4.54			O1	< 0.75	3.5 - 4.5					
3	4.54 - 6.35					4.5 - 5.5		1-4	3.5 - 7.5		
4	6.35 - 7.26	N2	3.5 - 12			5.5 - 7					
5	7.26 - 8.85			O2	0.75 - 3.5	7 - 8.5	3.5 - 18	5	7.5 - 8		
6	8.85 - 11.79					8.5 - 10.5		6	8 - 10		
7	11.79 - 14.97					10.5 - 12.5		7	10 - 12		
				O3	3.5 - 10	12.5 - 16		8	12 - 14	1	< 20
8a	14.97 - 27.22					16 - 20		9	14 - 16		
						20 - 25	18 - 27	10	16 - 20		
						25 - 31	27 - 35	11	> 20		
		N3	> 12				35 - 40				
							40 - 43			2	> 20
8b	> 27.22			O4	> 10	> 31	43 - 46				
							46 - 49				
							> 49				

Fig. 3 Trucks classification schemes (source: IEA, 2017)

2.2 Benchmarking national emissions' regulations

As introduced before, different legislations have been enacted in recent years to incentivise the transition from conventional ICE (internal combustion engine) vehicles to electric ones. Governments around the world have adopted different combinations of emissions standards, incentives and tax reductions to meet the Paris agreement target. Although in this section the different frameworks will be presented to stress the disparities existing between them, a common strategy can be derived from those approaches. In 2018, the International Transport Forum[2] conducted a research between 108 experts of the boards of various associations and committees, ranging from government's organisations to private companies, academia and research institutes, and international NGOs. Among the many trends and opinions identified by this survey, a very interesting result was the different policy priorities for road freight decarbonisation in different countries. In figure 4 the results of the survey are summarized, and it is evident how all high-income countries are adopting a similar approach: banning certain vehicle types (e.g. limited traffic zones), introducing stricter emission limits and setting pricing mechanisms, such as CO_2 taxes and distance-based toll systems. Instead, an unexpected finding

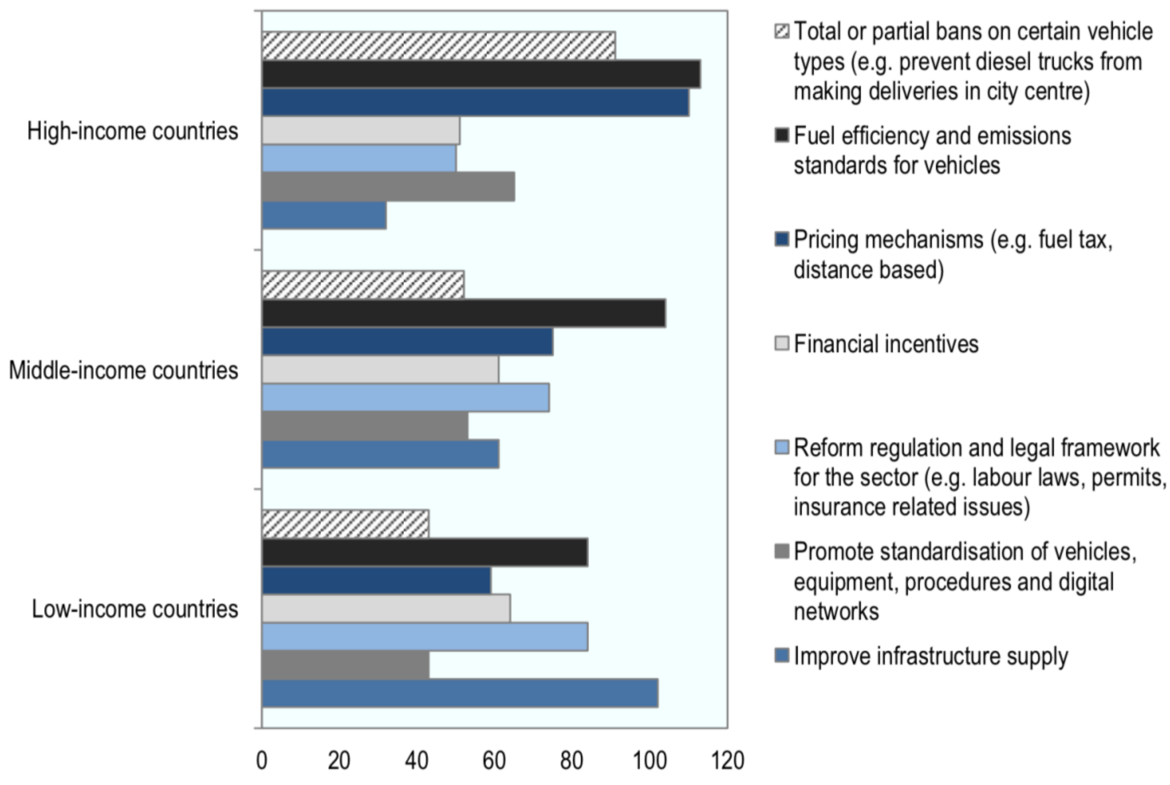


Fig. 4 Policy priorities (source: ITF expert opinion survey, 2018)

2 Retrieved from: IEA (2018), "Global EV Outlook 2018: Towards cross-modal electrification", *International Energy Agency*

is that financial incentives are considered as a priority by less than half of the respondents. Albeit incentives and tax reductions are an expensive measure for governments, they could be used on a global scale to boost the adoption of alternative fuel vehicles during this first phase. Thanks to such economical spurs, deliveries and logistic companies would be motivated to join the transition by having lower cost of ownership (both fixed and variable) and the possibility to reach and/or cross limited access' areas (improving route efficiency and reducing delivery time). By doing so, the widespread adoption would trigger the aforementioned scale effect, reducing the cost of production for the manufacturer, which consequently would allow the government to reduce and even eliminate the incentives scheme without undermining the ongoing adoption of alternative fuel vehicles.

As a consequence of the weight segmentation of the commercial vehicles' market, the emissions' standards will be analysed accordingly to the vehicle category they regulate. Starting from LDVs, global greenhouse gas (GHG) emission and fuel economy standards have been introduced, significantly, merely during the last decade. Up to a bit more than ten years ago, according to Yang & Bandivadekar (2017), only four governments had already introduced emission standards: Japan, US, China and South Korea. As of 2017, six countries joined these pioneers, including the European Union and Canada, all being part of the top 15 vehicle markets worldwide, raising the percentage of regulated LDVs to 80% of the global market. Unfortunately, these standards are not directly comparable, since they differ in ways that affect how vehicle performance against standards is measured—for example, different test procedures require a vehicle to be tested in dissimilar conditions over a dissimilar operating range. Additionally, the impact that the regulations will have on the emissions will vary on a national basis, due to the dependence on the customer preference on the size of the car, the engine power and fuel, specific driving habits and many other factors. In 2004 the Pew Center on Global Climate Change attempted for the first time to perform a comparison between the different national legislations. This experiment was then refined by the ICCT in 2007 and then in 2017 the same institution published a global update of that document, that will be used as main reference in this dissertation's section.

Before analysing and stressing the differences between the various standard schemes, it seemed important to highlight the first step towards a common evaluation model, carried forward by Japan and the European Union. According to the Global Update of the ICCT (2017), both countries planned to switch, by 2018, to the Worldwide Harmonised Light Vehicle Test

Procedure (WLTP) test cycle. This laboratory test was developed by the United Nations Working Party on Pollution and Energy (GRPE) to measure fuel consumption and CO2 emissions from passenger cars, as well as their pollutant emissions. It will also be used to calculate the energy consumption values of alternative powertrains, as well as their range, allowing to have a harmonised judging criterion, no matter what fuel the vehicle uses. Even though it will still not be able to simulate all variations of the driving conditions, it claims that it will provide a far more realistic representation of conditions encountered on the road, compared to the outdated simulations used before. The latter test values were based on theoretical driving profiles, while the WLTP cycle was developed using real-driving data, gathered from around the world, with the active contribution of the EU manufacturers. One of the key features is the fact that it is a dynamic cycle, taking into consideration much more driving phases and conditions compared to single test such as the previous New European Driving Cycle (NEDC). For the complete list of differences between the NEDC and the WLTP, a summary table is annexed (Exhibit 2).

In figure 5 can be seen the result of the ICCT's global update mentioned before and it is evident how national regulations differ on many different aspects. In particular, policymakers face a

Country or Region	Target Year	Standard Type	Unadjusted Fleet Target/Measure	Structure	Test Cycle
Canada	2016 2025	GHG	293 gCO_2/mi[1] N/A[2]	Footprint-based corporate average	U.S. combined
China	2020	Fuel consumption	6.9 L/100km	Weight-class based	NEDC
EU	2017 2020	CO_2	175 gCO_2/km 147 gCO_2/km	Weight-based corporate average	NEDC[4]
Japan	2015 2022	Fuel economy	15.2 km/L 17.9 km/L	Transmission, vehicle structure, weight-class based corporate average	JC08[4]
Mexico	2016	Fuel economy/GHG	29.7 mpg or 185 g/km	Footprint-based corporate average	U.S. combined
Saudi Arabia	2020	Fuel economy	13.2 km/L	Footprint-based corporate average	U.S. combined
South Korea	2020	Fuel economy/GHG	15.6 km/L or 166 gCO_2/km	Weight-based corporate average	U.S. combined
U.S.	2016 2025	Fuel economy/ GHG	28.8 mpg[3] and 298 gCO_2/mi 40.6 mpg[3] and 202 gCO_2/mi	Footprint-based corporate average	U.S. combined

[1] In April 2010, Canada announced a target for its LDV fleet of 246 g/mi for model year 2016. The separated targets for car and light truck fleet are estimated by ICCT based on the overall target.
[2] Canada follows the U.S. standards in the proposal, but the final target value would be based on the projected fleet footprints.
[3] Assumes manufacturers fully use low-GWP A/C refrigerants credits
[4] EU and Japan plan to switch to WLTP by 2018.

Fig. 5 Overview of regulation specifications for LDVs (source: ICCT, 2017) series of choices when defining GHG standards: which metric to regulate, whether to set a single fleet-average standard or take a tiered approach, which attribute to base the target on (e.g., vehicle footprint, weight, class, engine size, or interior size), which test cycle to adopt and which year to target. Completing this list of countries, Brazil introduced a tax incentive scheme, called Inovar-Auto program, that targets manufacturers to meet the non-mandatory fuel economy standards, which are expected to achieve 12%–19% fuel consumption reduction from 2013–2017 (ICCT, 2017). It has to be said that in recent years, other countries around the world decided to adopt one of these regulations (instead of developing a new one) in order to reach the goal set by the Paris agreement. California instead merits a specific mention as the pioneer in adopting GHG emission standards, not only at the state level in the United States, but at the global level. In 2002 California enacted the first state law requiring GHG emission limits for motor vehicles and from 2004 onwards every new car sold in California must be a LEV (low emission vehicle) or better (ICCT, 2017). As a result of these efforts, the Environmental Protection Agency (EPA), independent agency of the United States federal government, has decided to adopt the California emissions standards by the 2016 model year, on a national level, and collaborates with its regulators on stricter national emissions standards for model years 2017–2025.

Before comparing the results obtained and long-term plans set by the different regulations schemes, the new standards proposed by the EU must be introduced. In November 2017 the EC came forward with its regulatory proposal for the third set of CO2 regulations (the first dates back to 2009, while the second to 2014). The 10th of October 2018 both the Parliament and the Council voted—against resistance from Germany, Hungary, Romania, and Bulgaria—also in favour of strengthening the European Commission proposal (Mock, 2019). The compromise, endorsed by EU member states the 16th of January 2019 and officially adopted the 15th of April of the same year[3], includes the following key elements:

- New LDVs CO2 emissions, on average, must fall by 15% before 2025 and by 31% before 2030. Expressed in NEDC terms, using as the baseline the current 2020 CO2 target of 147 g/km defined by the 2014 regulation, these reductions would translate into a target value of 125 g/km (2025) and 101 g/km (2030). In figure 6 is visible how the historical trend of CO_2 emissions is very promising and in line with the new enacted regulation.

3 Retrieved from: https://www.consilium.europa.eu/en/press/press-releases/2019/04/15/stricter-co2-emission-standards-for-cars-and-vans-signed-off-by-the-council/

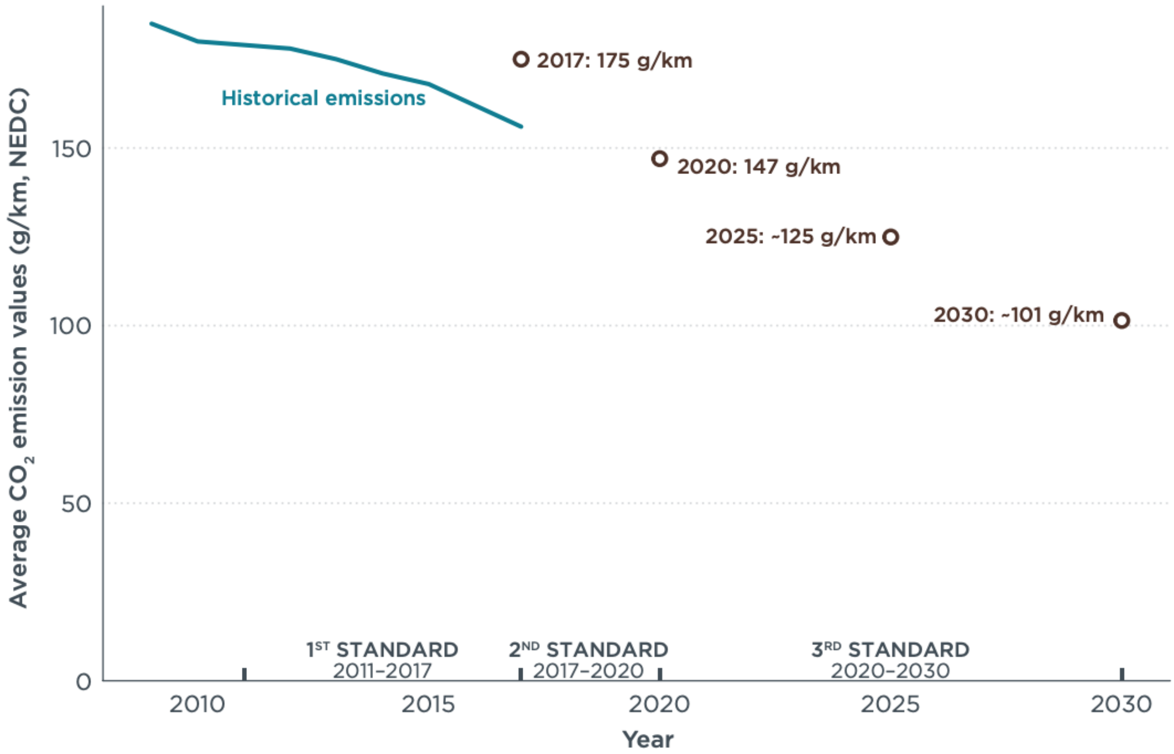


Fig. 6 Average historical and adopted standard's CO_2 emissions for LDVs in Europe (source: ICCT, 2019)

- The underlying utility parameter is defined as the vehicle weight, i.e., the heavier a manufacturer's LDV fleet, the higher that manufacturer's CO2 emission target will be under the regulation. Until 2024, a factor of 0.096 will be used, meaning that for every 100 kilograms (kg) by which a manufacturer's average vehicle weight exceeds the average EU fleet mass, 3.33 g/km higher CO2 emissions will be allowed. For determining the slope applied for calculating the annual manufacturer targets from 2025 onwards, the European Commission will carry out a least-squares fit through the CO2 vs. mass data of all vehicles registered in 2021.
- The post-2020 regulation defines zero- and low-emission vehicles (ZLEVs) as vehicles with CO2 emission values from zero up to 50 g/km. ZLEV sales targets for LDVs are set at 15% for 2025 and 35% for 2030, while some flexibility is granted to manufacturers in terms of how they reach those targets. For the purposes of the regulation, ZLEVs are counted proportional to their zero-emission capability: zero-emission vehicles count as full vehicles; vehicles with CO2 emission values with 51 g/km and higher count as zero; and vehicles between 0 and 50 g/km are assigned weights between 0.3 and 1 according to a linear function based on CO2 emissions. A manufacturer could thus, hypothetically, reach the target with a high proportion of plug-in hybrid electric vehicles in its 2025 fleet and few to no battery-electric—or vice versa.

For manufacturers that exceed the ZLEV target by 5 percentage points or more, the factor is equal to 1.05 (scaling proportionally for surpluses smaller than 5%), while for manufacturers that fail to meet the ZLEV target, it will stay equal to 1. A ZLEV factor higher than one, will increase the emission target of the specific manufacturer by a factor between 1% and 5%. Instead, there is no penalty for manufacturers not meeting the ZLEV sales targets (bonus scheme).

- While the percentage reduction targets in the CO2 regulation are fixed, the absolute CO2 emission level to be met in 2025 and 2030 depends on the fleet average WLTP starting point of all manufacturers in 2021, which is in direct correlation with the NEDC-WLTP adjustment factor. This factor will be determined for the 2020 new vehicle fleet for each specific manufacturer. In order to avoid manufacturers' inflation of their 2021 WLTP-NEDC ratio, by declaring unjustifiably high WLTP CO2 emission values, the EC determined that the 2021 CO2 baseline will rely directly on the measured values.
- The regulation introduces a mean of systematically monitoring of CO2 emissions under real-world driving conditions. Beginning this year, new LDV types will have to determine and store lifetime fuel-consumption and/ or energy-consumption values. Starting from 2020, all new LDVs (all new vehicles, not only new models) must be equipped with an on-board fuel and/or energy consumption monitoring device (OBFCM). Using data from those OBFCM units, from 2021 to 2026 the European Commission will monitor and annually report the gap between official and real-world CO2 emissions. No later than June 2023, the European Commission must assess how data from OBFCM devices may be used to prevent the real-world gap from growing.

This new standard scheme brings back the EU as one of the key players in the common effort to achieve the target set by the Paris agreement. As of 2017, when the aforementioned update was still just a proposal, the European Union was only the 4th main player, after Japan, US and Canada, as can be seen from figure 7. This highlights once more the fact that for commercial vehicles, other countries have been pursuing much more stringent and longer-term targets compared to the EU. Figure 7 is an extrapolation of the original comparison analysis of Mock (2019) for the ICCT and the data of the 3rd EU emission standards. Although the ICCT hasn't developed yet a comparison with the updated standard (has it has done for passenger cars, which graph is annexed in Exhibit 4), also due to the fact that other countries are currently reviewing

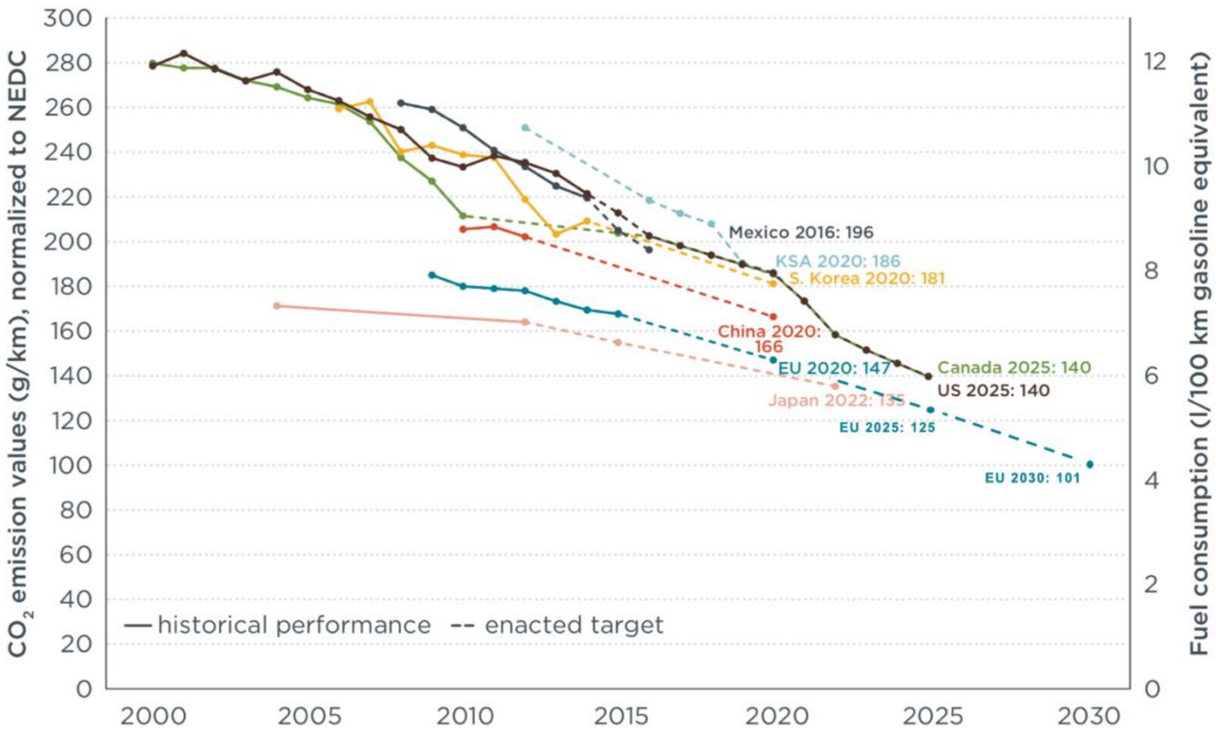


Fig. 7 Historical fleet CO_2 emissions performance and current standards for LCVs (adapted from: ICCT, 2017)

their regulations, this extrapolation gives an idea of why, both the EU Parliament and the Council, decided to strengthen the European Commission proposal. Additionally, on a national level, there are some countries such as Norway and The Netherlands which defined electric vehicle policy goals that will allow them to reach the EU targets many years in advance, at least for passenger vehicles and potentially also for LCVs. Although the ZEV (Zero Emission Vehicle) regulations are out of the scope of this section (for a matter of simplicity), they contribute in a massive way to the local attainment of the EU standards. As elicited by Hall et al. (2018) in the EV capitals article, Norway's cities of Oslo and Bergen are pushing the country towards the set goal of all new ZEVs by 2025. The Netherlands follow Norway's lead with a 100% Zero Emission Vehicles share by 2030, then France and UK by 2040 and finally Germany claims to reach this target before 2050 (in Exhibit 5 the complete graph).

Moving to the category of Heavy-Duty Vehicles (MDVs are regulated by the same standards due to their similar functionalities) the situation is much more delicate and alarming. Regulations in this sector are much more recent, which means that they tackle only the preliminary phase of the transition toward sustainable HDVs and will need many more updates in the years to come, and they are also less widespread compared to LDV standard. This discrepancy may be imputable to the fact that the LDV category includes passenger vehicles, which are a priority for policymakers at the moment. Nonetheless, it must be kept in mind that, according to the research of Delgado and Rodríguez (2017), Heavy-Duty Vehicles in 2015 accounted for 19% of the CO_2 emissions of the transportation sector and 6.1% of all direct CO2 emissions in the European Union (see Exhibit 6 for the complete infographic). According to the same publication, despite mandatory CO2 targets for new LDVs, transportation is the only sector that has not reduced CO2 emissions in recent years. A possible cause may be found in the increase in passenger and freight transportation demand, which leads to a growing vehicle fleet and an increasing number of kilometres travelled by those vehicles. Additionally, there are some prevailing market barriers, and market forces alone are not enough to guarantee technology adoption. Out of these, the most important ones are: uncertain return on investment, due to a lack of credible information on the real-world performance of new technologies, upfront capital costs, split incentives (when the entity buying the technology is not the same entity that accrues the fuel-cost savings) and, in certain markets, lack of technology availability. In the light of these market inefficiencies, several countries around the world have already introduced CO2 standards for HDVs. Japan established the first mandatory fuel-efficiency standards for HDVs in 2006, with a "top-runner" approach, meaning that the performance of the best vehicles in the market was used as baseline for the definition of the standard. Due to resulting limited engine modifications and modest emissions reductions of 1.2% per year, a second stage was proposed in 2017. It targets 13-14% reductions on average for trucks and buses and incorporates additional technologies such as aerodynamics and tires. According to Delgado and Rodríguez (2018), the U.S. Phase 1 and Phase 2 GHG standards for HDVs are the most comprehensive standards yet, even including separate standards for engines and trailers. The phase 1 standards were enacted in 2010, regulating model years 2014 to 2018, while the phase 2 standards, enacted in august 2016, regulate model years 2018 to 2027. According to the aforementioned ICCT paper, the highest fuel-consuming segment, tractor-trailers, will see reductions of about 50% in 2027. China followed in 2012 with the first of three stages of progressively more stringent standards. The proposal for stage 3, scheduled to take effect this year, introduces tighter fuel-consumption limits of an additional 12.5-15.9% compared to the previous standard. At last, in 2017 India finalized its first fuel-efficiency standards for commercial HDVs. Phase 1 goes into effect in 2018, and Phase 2, in 2021, with target reductions of around 11% on average. The targets are gathered in figure 8 to allow a preliminary comparison of the reductions required by the standards, also for the EU proposal that will be discussed in the following paragraph.

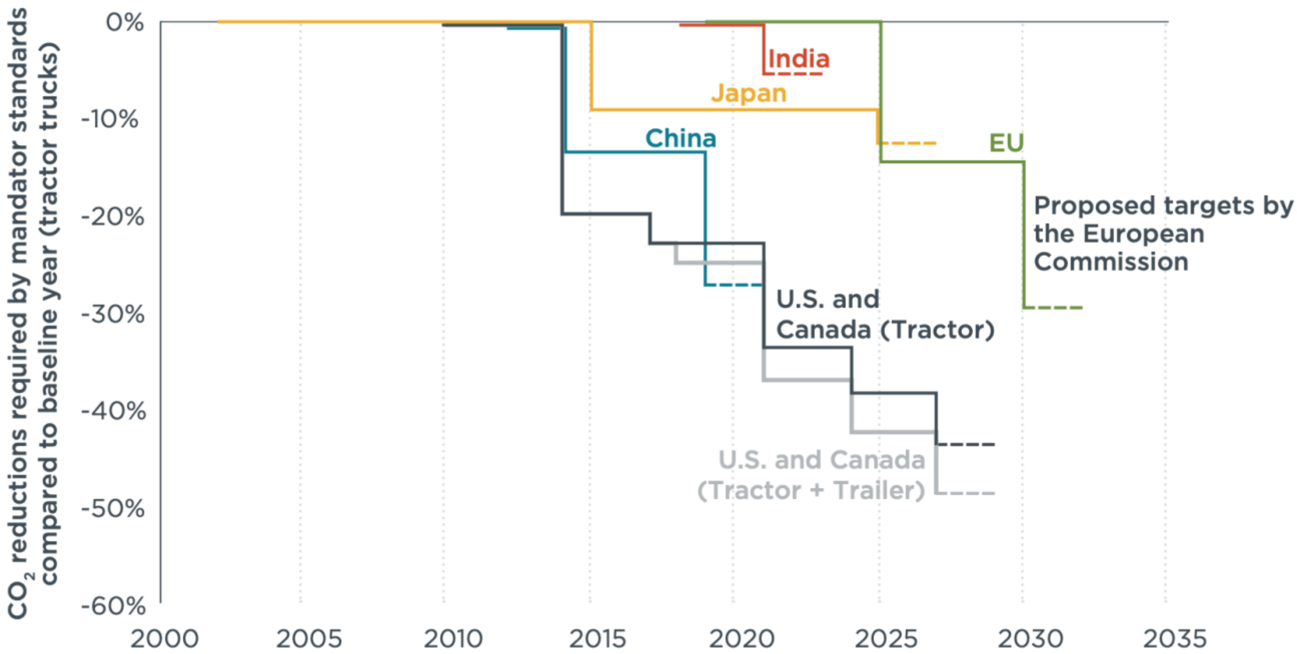


Fig. 8 Tractor-truck standards around the world relative to the baseline in the 1st phase of the standards (source: ICCT, 2018)

At the time of the quoted publication, the European Union was the largest HDV market without any mandatory limits of CO_2 emissions for such vehicles. A few months later, the 17th of May, 2018 the European Commission issued a regulatory proposal that would set initial carbon dioxide (CO2) emission standards for new heavy- duty vehicles (HDVs) sold in the European Union. At the end of this legislative process the EU will become the sixth government to regulate tailpipe CO2 emissions from trucks. The complete list of the key elements of the EU proposal, together with the HDVs classification of HDVs for the purpose of certification, can be found in Exhibit 7 and 8. The proposal regulates only four categories out of the listed ones, identified by the Commission as those responsible for over 65% of all CO2 emissions from EU's HDV fleet. Even though the standard sets stringent limits to CO_2 emissions in line with Chinese ones (although 10 years later), it is far from what is needed to reach the Paris agreement target. The policy update of the ICCT by Delgado and Rodríguez (2018) identified that, the EU could meet the short-term targets for non-ETS sector by 2030 with a CO2 reduction for new LDVs and HDVs greater than 40%. But anything less than 40% for HDVs would require the targets for LDVs to become more stringent. In the long-term, if the EU is to meet its obligations under the Paris Agreement, it must achieve a greater than 70% CO2 reduction for LDVs and close to 50% for HDVs by 2030, as can be seen from Exhibit 3. In the next paragraph, using as reference the aforementioned policy update, some key pitfalls of the proposal will be highlighted.

The first identified issue concerns the regulated categories. Including HDV engine standards would have been an effective wat to indirectly cover, at least partially, all the vehicle categories out of the scope of the standards. It would also send a very strong message to encourage long-term investments in the R&D of engine efficiency improving technologies. Additionally, all the HDV that are not intended for delivery purposes, defined vocational trucks which include refuse collection trucks and construction vehicles, are excluded from the scope of the standard. The CO_2 certification of vocational trucks is left at discretion of the manufacturers, which will have the power to define which vehicles will automatically be out of the scope of the proposal. Secondly, the regulation introduces a system of incentives, in the form of super-credits, to incentivize the adoption of zero and low emission heavy-duty vehicles (ZLEVs). A multiplier, the ZLEV factor, is used in the calculation of the manufacturer-specific average CO2 emissions, based on the number of ZLEVs sold by the specific manufacturer. The multiplier factor ranges from 2, for ZEVs, to 1, for vehicle emissions of 350 gCO_2/km, which is the limit definition of LEVs, being the latter category super-credit variable between the two bounds according to the specific emission level. This scheme allows ZLEVs to be counted as more than one vehicle (up to 2 for ZEVs), in the calculation of the fleet-specific average emissions. Being this factor at the denominator of the average, it can reduce substantially the overall manufacturers emissions, constituting a big incentive for investments in ZLEVs. Being said that, the proposal does not take into account differences in annual mileage and payload between the different subgroups. By doing so, this system disincentivizes efforts for freight vehicles that transport high payloads over long distances, as they face greater challenges in transitioning to ZLEV technologies but receive no greater benefit than smaller urban ZLEVs. Another potential mistake of this matter was including in the ZLEV factor scheme also non-regulated heavy-duty vehicles. By doing so, manufacturers of buses for example (which are already strongly transitioning towards electric vehicles, such as Volvo buses) will benefit from super-credits without being subject to any stringent emission standard. Last but not least, the baseline used for the definition of the standards is controversial and brings a degree of uncertainty in the evaluation of manufacturers compliance to the set targets. Using the 2019 data from the monitoring and reporting regulation as the regulatory baseline means that the value will remain unknown until 2020, when the numerical value of the baseline is determined. Additionally, this method gives to the manufacturer direct influence on the baseline through their product portfolios, and thus on the benefits of the standard. Hopefully, the mid-term review programmed for 2022, depending on its outcome, will adjust the regulatory design and stringency of the standards for 2030 onwards.

As anticipated, China historically implemented emission standards in line with those of the European Union, with implementation dates anticipating the latter by 8 to 10 years. This allowed China, up to the current standard, to be as stringent as the US and Canada for HDVs CO_2 emission regulations, as can be seen in figure 8. In order to do so, the last enacted standard, China VI, released the 28th of June 2018 by the Ministry of Ecology and Environment (MEE), will combine both best practices of EU and US regulations and create its own requirements (Yang & He, 2018). The new standard will be implemented in two phases, both characterised by implementation dates progressively including a broader set of HDVs categories: China VI-a, with eventually regulate all HDVs by 2021, while China VI-b will affect all new HDVs starting from 2023. Although China VI-a is largely equivalent to EURO VI standards (the one illustrated in the previous paragraph), China VI-b introduces slightly more stringent testing requirements and a remote emission monitoring system. Particularly, as described by Yang and He (2018), the standard key features will be:

- Reductions in nitrogen oxides (NOX) and particulate matter (PM) emission limits by around 70% from the current China V standard
- A shift in the test cycle, from the old European Steady-state Cycle (ESC) and European Transient Cycle (ETC) to the more dynamic and representative of real driving conditions World Harmonized Stationary Cycle (WHSC) and World Harmonized Transient Cycle (WHTC); additionally, the new World Harmonized Not-to-Exceed (WNTE) test will be included
- Adoption of full vehicle Portable Emission Measurement System (PEMS) testing and requirements based on the European PEMS regulation, although tailored to the unique driving conditions of China
- Improved on-board diagnostic (OBD) system and anti-tampering provisions based on U.S. OBD requirements; additionally, every vehicle will be required to be equipped with a remote emission monitoring on- board terminal (remote OBD), a first in vehicle regulation across the globe;
- China's first emission warranty program for HDVs, in which manufacturers are required to guarantee emission-control parts for a minimum distance travelled or service time.

As stressed in the LDVs paragraphs, it is remarkable how Europe is not the only country shifting towards the adoption of worldwide harmonised test cycles, which will allow the standards and their compliance to be comparable on a wider scale. The difference with respect to the EU standards is mainly imputable to correction of the PEMS test. As shown by the research of

Muncrief (2015), which gathers several studies on the HDVs emissions under E IV, V and VI regulations, these HDVs produce substantially higher NOX emissions during real-driving conditions than of the type-approval test cycles. To correct this discrepancy, China VI introduces additional PEMS tests for new and in-use China V standard certified HDVs. In Exhibit 9 can be found a direct comparison of the different worldwide adopted standards through their conversion in terms of Euro VI equivalence.

Even though the trends expected form the implementation of the aforementioned regulations and the first results measured are really promising and show a strong decreasing trend of average emissions in the transportation sector, they are still not enough to reach the Paris agreement's targets. As it has been determined by the ICCT (2019), the current enacted and proposed standards for both LDVs and HDVs (which will be introduced in the following paragraphs), will still not be able to stay below the two degree Celsius scenario (as can be seen from the graph annexed in Exhibit 3). The research of Lutsey (2018) identified how efficiency standards are not sufficient, even though essential to launch a mainstream electric vehicle market. The strongest possible policies under consideration will deliver up to 5% electric share in the United States, 11% in Europe, and 20% in China by 2025, being the latter already the biggest market of electric vehicles, with about half of the global sales. On a global scale, this would correspond to less than world's vehicle sales being electric in 2025. Although such measures will incentivise investments in research and development of EVs, resulting in wider vehicle model availability and costs reductions, it will still not spark the inevitable transition, nor bring profitability beyond a few market leaders. Ensuring the transition to electric by 2050 will need much stringent and bolder standards or direct electric vehicle requirements. In many countries the targets and pledges of decarbonization by mid-century are not reflected by the regulation implemented to achieve them, which are not yet steered in that direction. By the mid-2020s, regulations will have to pivot from using artificial electric vehicle incentives—for example, multipliers, to using real EV development and sales' requirements and put markets on a path toward decarbonization. With electric vehicles becoming cost-effective from 2025 on, thanks to lower cost of batteries and economies of scale expected to play a stronger role, much more rapid gains are possible (Lutsey, 2018). It still has to be pointed out that these standards and regulations are constantly under review and updates are usually proposed just a few years after the approval of the current one. In fact, from the graph in Exhibit 3 it can be seen how, in correspondence of each new standard, the negative slope of the trend increases every time, which can justify a certain optimism in the proposals to come.

3 BUSINESS REQUIREMENTS

The objective of this thesis is to identify the available technology that matches the user requirements and to analyse its costs, for both the manufacturer and the final customer. Before reviewing all the different available technologies, a brief introduction of what are the user requirements is needed, so that the following analysis takes already into account which need each technology will be able to satisfy. The first parameter to be taken into account when talking about electric vehicles, is the range of their batteries, or the capacity of the fuel tank when talking about alternative fuel vehicles in general. In fact, even though freight vehicles are differentiated on a gross weight-basis, they could be categorised also using as parameter the average distance travelled. In fact, weight and distance travelled are in a direct correlation. Heavy-duty vehicles are usually employed for international logistics' activities, to transport big quantity of goods and raw materials from the manufacturing plant to the final user or from the resource extraction site to the inventory of the production one. This allows to strategically distribute production plants around a specific continent and shift a big portion of the costs to the distribution of the final product to the final destination as to increase the margin of the manufacturer. Light-duty vehicles instead will be used for last-mile delivery, such as mail and post office, or for completely different kind of services such as construction, garbage collection, transportation of tools and utensils for independent workers and many other. Finally, medium-duty vehicles will have requirements in-between the two boundary categories, depending on their application in terms of business sector. The specific industry of application will influence the type of materials to be transported, hence the gross-weight of the vehicle, and the distance needed to be travelled. According to the Italian Ministry of the Environment (2013), vehicles used for last mile delivery travels on average between 30 km and 70 km, while long-haul trucks distance travelled will depend on the final destination. When transporting goods within Italy, heavy-duty vehicles will travel on average 102.5 km per day, whereas for international shipping the average distance jumps to 727.4 km per day. This will also directly influence, for the case of PEVs and PHEV, the maximum or average distance between charging stations. For example, applications in the delivery services industry allows charging stations to be installed in the different warehouses around the urban area, since the LDVs could be charged while waiting to be loaded and consequently have a smaller battery.

The installation of smaller battery packs directly introduces the second key requirement, that is the weight. The classification of freight vehicles was done using the gross-weight parameter, rather than the curb-weight, because the load weight plays a key role in the engine size, consumption of the vehicle and size of the tank required. In case of an electric MDV or HDV (it will be seen that the state of the technology does not allow yet a pure-electric HDV), the size of the battery will not be a direct influence on the performance of the vehicle since it will be negligible compared to the gross-weight of the whole vehicle. Contrariwise, for an LDV, the weight of the battery pack must be carefully taken into consideration to avoid a big increase of the total gross-weight and consequently a reduction in the vehicle's efficiency. It can be derived that the engine's power can be a direct consequence of the vehicle's weight, even though the distance to be travelled will influence as well in its calculation. The engine must be sufficiently powerful to move the trailer (in case of HDVs and MDVs) or the load and to reach the necessary speed of the road to be taken (e.g. highways require a minimum speed), while at the same time ensuring the minimum fuel consumption possible.

Finally, there are "secondary" parameters to be taken into consideration when defining the business requirements. First of all, for LDVs, accessibility is a very important factor since the vehicle must be able to take the shortest or fastest path to the final destination to avoid unnecessary fuel consumption. Particularly in the last decade, very polluted cities have introduced limited traffic zones to reduce the concentration of GHGs in the air. This creates a strong incentive to the adoption, for all uses of LDVs, of electric vehicles since they are allowed to enter limited traffic zones, normally, without paying extra fees. Second very important parameter is the time required for a full charge for the batteries and is one of the key discrimination factors for the adoption of electric vehicles. While alternative fuel vehicles are just limited by the availability gas stations, of their specific fuel, electric batteries need much more time to be recharged and, depending on the charging infrastructure and the size of the battery, this factor may delay the transition to the adoption of EVs. Last but not least, the price of EVs is a key factor and has been, historically, one of the main barriers to their widespread adoption. Particularly for SMEs, the additional costs to be incurred when buying an electric vehicle, which include the upfront investment for the charging infrastructure and the higher price of the vehicle itself, have historically being prohibitive, albeit in a few cases incentives allowed the EV sales to grow anyway. It will be shown how, thank to external factors such as the decreasing cost of batteries, there are now many situations in which electric vehicles became a cost-effective solution.

4 STATE OF THE ART TECHNOLOGY

As elicited by the International Energy Agency (2017) "there is a wide range of operational modifications in road freight that can translate to efficiency improvements, while increasing bottom-line profitability by driving down shipping costs". In fact, many improvements in the logistic industry, and operations field in general, are related with all the management and planning activities, rather than the vehicles themselves. As a matter of fact, the aforementioned research of the IEA identified a series of possible measures and it seemed reasonable to introduce them, even though the improvements that they would bring are small and just complementary to the adoption of alternative fuel vehicles. Nevertheless, since they affect how the vehicles are driven, they influence anyway the overall efficiency of the vehicle, even in the case of a complete transition to electric freight vehicles. These actions can be grouped in three macro-categories along the whole delivery process, which are: the transportation of the goods, the delivery to the final customer and the planning of the logistics overall.

The first group of measures is related with the possibility of improving the transportation process. The first procedure suggests the introduction, or higher use, of high-capacity vehicles (HCVs), to exploit the fact that the relationship between the gross vehicle weight (GVW) of a truck and its fuel consumption is not one-to-one. It means that an increase in a truck's size and payload leads to a smaller proportionate increase in fuel consumption, as can be seen from the analysis performed by the IEA (2017) in figure 9, using the World Harmonized Vehicle Cycle.

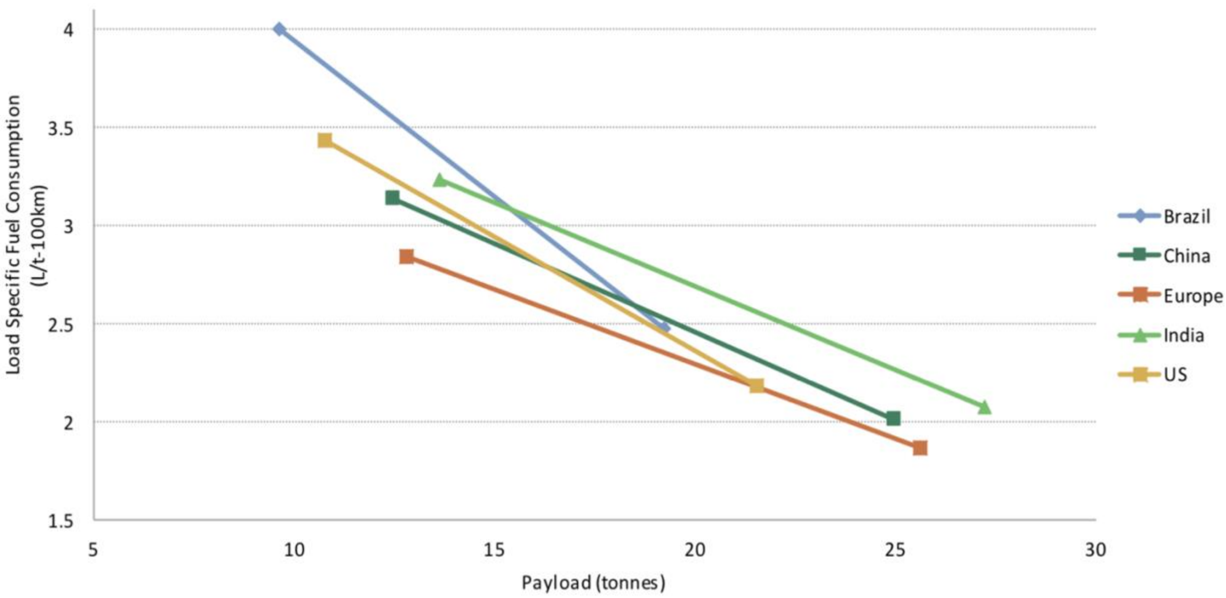


Fig. 9 Relationship between truck laden weight and fuel consumption (source: IEA, 2017)

In almost every country, there are regulations limiting truck size and weight, particularly to limit wear and tear on roadways and bridges and to address safety concerns. Revising these restrictions in favour of a framework permitting the use of HCVs would allow to increase the efficiency per trip and consequently reduce the overall fuel consumption per tonne of goods transported. A second and more conventional measure would be route optimisation, which is self-explanatory. Finally, a very innovative concept introduced is "platooning", which will heavily depend on the development of automation technologies and communication with other vehicles and traffic authorities. Practically, it refers to the practice of driving heavy-duty trucks (primarily tractor-trailers or rigid trucks) in a single line with small gaps between them to reduce drag and thereby save fuel during highway operations. Vehicle-to-vehicle and vehicle-to-infrastructure (V2V and V2I) communication technologies can enable trucks to drive in very close proximity without sacrificing safety or manoeuvrability. It is evident how the introduction of autonomous driving trucks and artificial intelligence in this industry could bring platooning as a direct consequence[4].

Moving to the final delivery phase, there are two very interesting possibilities. The first one is introducing last-mile efficiency measures, which would be enabled by the introduction of prediction algorithms of dynamic demand. This practice would allow to prepare for and smoothen seasonal and daily peaks. Examples of such solutions include "click-and-collect" options, meaning the possibility of collecting the package in a selected store and the use of lock-boxes in shops and gyms. With the growth of online retail and demand for "just-in-time" delivery, the relevance of last-mile deliveries is set to grow. It has to be pointed out that, in case of the introduction of specific regulations allowing their widespread use, drones could solve this problem in a very efficient and customer-centric way. A second factor that could be manipulated is the timing of the delivery, by shifting it in the off-hours or night-time. An essential condition for the success of such procedure is to provide incentives to shipment receivers (e.g. stores and retail outlets) to accept the insurance and logistical impacts of shifting to early morning deliveries. The IEA (2017) estimated that, in cities such as New York, Bogotá and São Paulo, the reduction of congestions and traffic in general brought by this measure would lead to a reduction in local pollutants in the range of 45-67%. In general, across the urban

[4] According to Tsugawa, Jeschke and Shladovers (2016), the average fuel saving for three trucks driving at 80 km/hr with a 10-m gap is about 8%, and 15% with a 4-m gap. High levels of vehicle autonomy would be needed to safely operate trucks with a 4-m gap.

LCV and MDV fleets CO_2, emissions reduction would be more conservatively estimated in the range of 10-15%.

Finally, there are measures that can be applied at an upper level of the supply chain, which means actions meant to change how deliveries and logistics are strategically planned. The first of such measures is called “improved vehicle utilisation” and is the idea of increasing the vehicle capacity utilisation. On average, vehicles are operated below full cargo weight: according to the IEA (2017), when laden, trucks may carry only about 40-60% of their maximum rated payload. For example, in some cases operations are volume constrained, rather than weight, which is the case of very big single components (e.g. the energy sector requires very big parts which are preassembled and then moved to the final site). The other possible cause of inefficiencies of the vehicle capacity utilisation is called “empty runnings”. As derived from Eurostat (2018), analysing the percentage of vehicle-kilometres recorded as empty in 2017, one fifth of the journeys of freight vehicles in the European Union were performed by empty vehicles. Member states fell on average in the 15% - 30% range, with just 3 countries able to stay below the 10% threshold: Denmark, Belgium, Luxembourg. Even though this may seem as a normal consequence of the operations activity, it may create huge inefficiencies for bigger countries such as the US and China, where the average distance to be travelled from the production site to the selling point is much longer compared to the EU. Maximisation of the loads carried by trucks can generally be achieved both via internal logistics improvements and through external (i.e. across-firm) collaboration. The latter case is the most interesting one, since its effects would be visible at a wider scale and overall the fuel consumption reductions would be higher. A first solution in this sense would be “backhauling”, refers to the practice of delivering cargo on return trips, thereby offsetting other trips, which would drive down “empty runnings”. Albeit time constraints are the major barrier to carriers taking advantage of backhauling, due to non-synced operations between different manufacturers and logistic services providers, relaxing scheduling constraints would be an effective way to promote the practice. Instead, a measure to directly increase the capacity utilisation in each trip would be “co-loading”, which refers to bundling shipments across product categories with similar shipment characteristics (e.g. destination and time constraints). This would allow to trigger both economies of scale (e.g. route planning and route optimisation would be more effective thanks to a bigger number of delivery destinations) and of scope (e.g. warehouses facilities could be shared as well). Even though, on average, the unit throughput time will eventually increase, the global effect, considering all goods delivered in a single trip, is a very big reduction in fuel consumption. It straightforward that, in both cases, all information on destination, time constraints and standardised data on weight and volumes must be shared, by all firms, on a common platform as to make this measure the most effective. The last measure proposed is the translation of the previous one at the urban level and is called “urban consolidation centres” (UCCs). The idea consists grouping shipments from multiple shippers and retailers and consolidating them onto a single truck for delivery to a particular geographic region. It could be enabled by the introduction of regulatory policies to reduce congestion and promote air quality within the urban area. According to the research of Allen et al. (2012), vehicle activity and CO2 emissions within urban centres can be reduced by an estimated 30-80%.

This brief introduction had the objective of stressing the importance of improving the overall efficiency of the whole supply chain, rather than just reducing the fuel consumption of the freight vehicle itself. It has to be kept in mind that such measure would play a bigger role in the case of alternative fuel vehicles, such as biofuels and hydrogen, for which the fuel consumption reduction would both decrease the vehicle’s emissions and bring a great reduction of the operational costs for the logistic services provider. Contrariwise, for pure-electric vehicles, the marginality of the advantages of such measures would reduce, since they would only reduce the consumption of the battery capacity. It shouldn’t be misinterpreted as an irrelevant effect, since many of these measures could bring many indirect effects resolving issues such as charging stations and range needed. An example of such advantages would be that, by sharing the logistics activity with other firms would both introduce many intermediate stops for short charging of the batteries (in the case of co-loading) and reduce the upfront investment cost of adopting electric vehicles for the single company. The objective of the following sections is giving an idea of the state of development of the different technologies available and the expected trends in terms of their widespread adoption and the related costs.

4.1 Short-payback improvements

This section is dedicated to a short briefing of the technologies already available, and in some cases in use, for the improvement of vehicle performance, that present payback periods shorter than three years. The research of the International Energy Agency (2017) is used here as a reference, explaining in detail each identified solution as shown in figure 10. These examined

Measure	Description	Potential energy savings
Aerodynamics	A wide range of aerodynamic fittings (such as aft box tapers, aerodynamic tractor bodies, mud flaps, trailer tails, box skirts and cab/box gap fairings) can reduce the drag coefficient, thereby reducing road load.	Individual vehicle components reduce fuel use by 0.5-3%, depending on the truck type and aerodynamic retrofit.
Low rolling resistance (LRR) tyres; **Tyre pressure systems (TPS)**	LRR tyres can be designed with various specifications, including dual tyres or wide-base single tyres with aluminium wheels, and next-generation variants of these designs.	The potential ranges from about 0.5% to 12% in the tractor-trailer market. TPS alone could reduce fuel use by 0.5-2%.
Light-weighting	Broadly, all HDV vehicle types except utility trucks could cost-effectively reduce weight by upwards of 7% within the next ten years.	The CO_2 savings potential is about 1% by 2020, 2-3% by 2030 and 2.7-5% by 2050.
Transmission and drivetrain	Moving from manual to automatic/automated manual transmission can greatly improve efficiency. Adding gears, reducing transmission friction and using shift optimisation in manual automated or fully automated transmissions can also improve drivetrain efficiency.	Automatic/automated transmissions reduce fuel consumption by 1-8%, depending on truck type; other improvements lead to fuel savings of about 0.5-2.5%.
Engine efficiency	Engine improvements include increasing injection and cylinder pressures, both of which typically improve incrementally on a yearly basis.	Improvements in the coming decade could lead to fuel savings of approximately 4% (in service/delivery vehicles) to 18% (in long-haul trucks).

Fig. 10 Vehicle efficiency measures with short term net savings (source: IEA, 2017)

measures are all commercially available for a variety of freight vehicles' categories, from urban services and delivery vehicles up to long-haul heavy-duty trucks. The potential fuel savings shown in the table are based on the total cost of ownership over three years and they vary in the indicated range depending on the specific vehicle-mission category. The study estimates that the overall energy savings span in the range that goes from 10%, for urban delivery vehicles, up to 30% for long-haul trucks (IEA, 2017).

The first two potential improvements are focused on reducing the two most important road-load forces acting on a freight vehicle, particularly for HDVs travelling at high speeds:

- Aerodynamic drag force, depending mainly on the cross-section area (geometry) and the square of the vehicle speed
- Rolling resistance, force that depends mainly on the vehicle mass and the rolling resistance coefficient of the vehicle's tires

The first drag force could be reduced adopting a wide range of aerodynamic fittings, such as trailer tails and box skirts. It would be a key measure for long-haul heavy-duty applications, since the drag is the main source of energy losses for this category, accounting for most of the tractive energy required at typical highway speeds (90-120 km/hr). The uptake of aerodynamic retrofits has been quite rapid in the North American fleet, being present on more than 80% of new tractors and trailers on average; on the other side, these technologies are far less widespread in the EU (IEA, 2017). The reduction of rolling resistance would be even easier and straightforward since tyre manufacturing companies are already heavily investing in new solutions to reduce the drag created between the tyre and the road surface. Depending on the various specifications (e.g. requirements of LDVs and HDVs vary a lot in this case), combination of dual tyres or wide-base single tyres with aluminium wheels have been developed in recent years. Additionally, automatic tyre pressure adjustment systems have been introduced not only to increase fuel economy, but also to guarantee additional safety on road. The reference paper of the IEA (2017) has been able to demonstrate that, in many of these mission segments, low rolling resistance (LRR) tyres consistently rank among the most cost-effective, fuel-saving measures available. The third proposed measure, which would also indirectly impact the rolling resistance due to its relationship with the vehicle weight, is the reduction of the GVW. In fact, the IEA (2017) determined that, thanks to materials substitution in the vehicle components of the chassis, suspension, cabin and other, all HDVs could achieve a 7% reduction in weight within the next 10 years, only adopting cost-effective measure. This number is expected to grow up to 30% in 2050, thanks to technological advancements, and bring a carbon reduction potential in the range 3-5% in the same timeframe.

The last two measures are related with the mechanical parts of the vehicle, in particular the transmission and the engine. A first takeaway, which has been studied during many years both on commercial vehicles and passenger cars, is the shift optimisation related with manual automated (AMT) or fully automated transmissions. The adoption pattern of the two different mentioned technologies heavily depended, historically, on the vehicle category and geography. A second solution related with the transmission and drivetrain is the possibility to decouple, when not used, all the auxiliary (cooling fan, air conditioner, power steering pumps) when not used. This would reduce the so-called "parasitic" losses that increase with engine speed. The last type of improvements concerns the reduction of all the losses that occur inside the engine. Usually, new models are characterized by smaller frictional losses thanks to low-viscosity lubricants and low friction coatings and finishes. They may also have optimised combustion chambers (increasing injection and cylinder pressures and improving fuel automation), exhaust reductions and improved thermal insulation of the overall system. A more innovative solution that is being developed recently, is the introduction of waste heat recovery (WHR) systems, such as organic Rankine cycles. While there is no truck currently on the market using WHR, R&D advances show technologies that could be integrated into new trucks within the next 5 years, allowing to save part of the energy lost as hot exhaust gases, which is estimated to be 45% of the energy converted in conventional diesel engines (Rodriguez et al., 2017).

4.2 Alternative fuels – Natural Gas

The diversification of the energy supply is a topic that is continuously discussed not only in the transportation sector, but also in the energy industry and domestic demand of energy, to avoid dependence on the importation of a specific resource from one single country, which would bring political and economic instabilities. For such reason, in the last decades, many alternatives to diesel and petrol engines have been developed to create a variety of solutions for alternative fuel vehicles. It seemed reasonable to provide an overview of all the different available technologies, rather than focusing on electric only, and comparing them in terms of performances, widespread use, adoption and development costs. It also a common belief that, as highlighted in the paper of Dalla Chiara and Pellicelli (2016), the most viable and probable scenario, at least in a preliminary phase, will be characterized by the presence of many different fuel solutions, hybrid, electric and fuel cell vehicles. The predominance of a single solution will depend on its future developments, the capacity to meet the specific business needs and the development of the infrastructure needed for its widespread use and in general, the capacity of the technology to overcome all the barriers to adoption. The most optimistic scenario would be one in which many sustainable, and possibly completely green, offerings will be available depending on the specific requirements they are asked to meet.

The first fuel to be analysed is natural gas, which has been gaining importance in recent years as it is confirmed by the development of many freight vehicles relying on this source of energy, such as Freightliner and Mack in North America and MAN and Iveco in Europe. The ignition engines in this case are designed to run either on a blend of diesel and methane, in proportions that will vary according to the manufacturer, which are called dual-fuel vehicles, or solely on methane, using positive ignition systems. In both cases, the methane in stored, in order to be a suitable transport fuel, in two different forms:

- Compressed Natural Gas (CNG): it has a much lower energy density than diesel, which means that, depending on the pression of the storing cylinder, required in-vehicle fuel storage volumes are up to six times higher. The refuelling can be done both using on-site compressors, suitable for companies with large fleets, or retail stations operating on heavily trafficked corridors (due to high costs of powerful compressors and storage vessels), which introduces partial losses due to temperature increases (20% in volume). CNG is used mostly by smaller trucks with less regular operations and/or lower annual mileage, such as LCVs and MDVs.

- Liquefied Natural Gas (LNG): has a higher energy density compared to CNG, which allow the cylinder to store just double the volume of LNG to deliver a comparable travel distance to diesel. Refuelling a truck with LNG can be achieved at similar speeds as gasoline or diesel, but it requires complex and specialised stations (e.g. cryogenic storage tanks, cooling systems, etc.), which increase a lot the investment cost of building the infrastructure. This solution is best suited for larger vehicles with high annual mileage due to the boil-off risk, which begins 5 days after being left unvented, requiring the vehicle to be driven regularly (IEA, 2017).

In general, dual vehicles adoption is limited by the issue of incomplete combustion of the methane. This phenomenon, which is called "methane slip", limits significantly the CO_2 emission benefits that are attributable to the lower carbon content of methane in comparison with diesel. In general, the two barriers to adoption which causes the geographical differences in penetration of natural gas truck are the availability of the resource (depending on the national abundance and/or distribution networks) and the cost, of natural gas (compared to diesel). Governments play a key role in influencing the attractiveness of switching to natural gas, since they can both influence the total cost of ownership, through incentives, subsidies, and taxation regimes, and the construction of networks and infrastructures by enacting public policies seeking to address environmental concerns. Globally, 27,4 millions[5] vehicles are in use, being Asia-Pacific the biggest market (particularly China), Latin America is the second (Brazil is one of the biggest markets of dual fuel vehicles) and Europe the third one (in particular Italy and Sweden), according to the IEA (2017). Out of those, only a small portion, corresponding to about 1% in 2015, is attributable to freight vehicles, with LCVs being half of those and the rest split between MDVs and HDVs. Recent developments, in addition to the introduction of stringent emission standards and new tax credits, have favoured methane's penetration in the in the truck industry in the US, China and EU. Furthermore, the price gap between LNG and diesel has been fairly consistent in the last decade. Even though there have been some fluctuations, such as the one following the 2015 drop in oil prices, the price of LNG was on

[5] Statistics available at: http://www.iangv.org/current-ngv-stats/

average 55% of diesel, on an energy equivalent basis (IEA, 2017). This allowed the adoption of natural gas fuelled vehicles to increase dramatically in recent years, reaching a peak of 11% in China in the 2010-2016 timeframe.

The incremental costs of CNG and LNG freight vehicles are mainly related with the storage tanks. Due to the technological requirements of LNG (keeping the fuel at very low temperatures), liquefied gas storage cylinders are much more expensive compared to compressed gas ones. On average, the cost increment of an LNG is double of the CNG one, ranging between 15,000 € for an MDV and 35,000 € for an HDV (IEA, 2017). The payback period will depend on the technology choice and the annual mileage, in addition to the price differential mentioned above. In conditions where the fuel price gap is narrow, and there are no instruments to avoid passing the costs of early fuel distribution infrastructure developments to the truck operators, the economic case for the use of CNG and LNG is less compelling. Furthermore, when taking into account all the issues related with methane, such as high global warming potential (in the near term), leakages such as those deriving from fracking (huge problem in the US), switching to natural gas trucks results in only minor reductions in well-to-wheel (WTW) GHG emissions. It still has to be taken into account that, thanks to the lower carbon content of natural gas, may provide some benefits at an urban and local level.

4.3 Alternative fuels – Biofuels

The case for biofuels is very strong and promising, thanks to high energy densities and, in many cases, compatibility with existing vehicle fleets and distribution infrastructure. Additionally, the production of such fuels is mature, and recent developments have been focusing in enlarging the resource base from which biofuels can be produced, in particular exploiting wastes. Out of the existing options, the most common and used ones are:

- Biodiesel, which can be produced form a variety of different feedstocks, such as animal fat, oil crop and used cooking oil (UCO). Consumption in road freight vehicles is mainly through blended forms, with fossil diesel, in concentrations between 5% and 20%, allowing high degree of compatibility with existing engines. Higher blends, up to pure biodiesel, allow higher CO_2 reductions, but require modifications to freight vehicles.

- Biomethane, that can be directly used in gas fuelled vehicles and is produced by treating biogas produced from the anaerobic digestion of high moisture content organic wastes.
- Hydro-treated vegetable oil (HVO), known under the name of "renewable diesel", can be produced from similar resources to biodiesel, and is characterized by the aforementioned major researches to widen the range of applicable waste and residue resources. HVO is technically a "drop-in fuel", which means that it can be used in unblended forms without modifications to diesel engines or fuelling infrastructure.
- Ethanol, which can be produced using conventional crop-based and cellulosic feedstocks, principally from corn in the US and sugar cane in Brazil (where dual-fuel vehicles running on ethanol are widespread between LCVs and passenger cars). This fuel can be used in HDVs within suitably adapted diesel engines.
- Power-to-X (PtX) are synthetic fuels produced combining hydrogen (e.g. from electrolysis) with carbon or nitrogen to produce both liquid and gaseous fuels. This solution is still not widely commercially available but has great potential thanks to increasing shares of variable wind and solar photovoltaic electricity within the power generation portfolios of many countries. The possibility of using the excess electricity from such resources (due to non-synced availability and demand) to produce PtX fuels is gaining interest in many applications, as a substitute of storage technologies.

Biodiesel is by far the most commercialized option for heavy-duty transport (IEA, 2017), thanks to the fact that, in its blended forms, it is a drop-in fuel and does not require investments in fleet modifications. The second most used biofuel is HVO, thanks to the consumption approval from several European HDV manufacturers. As a matter of fact, Nordic countries such as Sweden and Finland make it available at service stations, both as pure HVO100 and in blends with fossil diesel. Last but not least, biomethane production is very prominent in Europe, where 450 plants were in operations by 2015. However, in most cases, production from these is fed into natural gas distribution networks, hence mainly used for residential and energy production purposes, rather than being ring-fenced for transportation use.

Without any policy support, it's very challenging for crop-based biodiesel, HVO and ethanol to compete with diesel, giving the current low oil prices. Waste and residue feedstocks are typically available at lower costs than virgin vegetable oils, but they can present additional challenges in processing due to their variable composition and the presence of impurities. A big barrier to the widespread use of biofuels is the feedstock choice, strongly influencing the level of decarbonization offered when compared to fossil diesel. When taking into account the lifecycle GHG emissions, crop cultivation and land usage change must be taken into account to have a clearer idea of shifting to biofuel (particularly biodiesel and ethanol in this case) would mean. A big concern, particularly for crop-based applications using corn and sugar cane (between others), is the extensive use of land for their cultivation. This value is not only big in absolute terms, but also in contrast with the need for land to meet continuously growing demand of food (which additionally increases the price of crop-based feedstock). For such reasons, excluding niche fuels such as algal biofuels, which are still in a preliminary development phase, this solution would be interesting only if adopted in combination with other alternative solutions, as in the mentioned in the previous section.

4.4 Alternative fuels – Hydrogen and Fuel Cells

Hydrogen is probably the alternative fuel solution most discussed at the moment, since, potentially, could be the alternative (not necessarily substituting) to electric vehicles. In fact, depending on the production resource used (as will be seen later), hydrogen and fuel cell vehicles (FCVs) would fall in the broader category of zero-emission vehicles (ZEVs). Furthermore, such vehicles are to be considered electric vehicles using hydrogen stored in a pressurized tank and a fuel cell for on-board power generation. As happens for electric vehicles, the braking energy is also recuperated and stored in a battery, which optimizes the operational efficiency by reducing the peak demand from the fuel cell during accelerations. One of the big advantages of hydrogen, when compared to batteries, is its higher energy density. In fact, as derived from the joint study of Shell and the Wuppertal Institute for Climate, Environment and

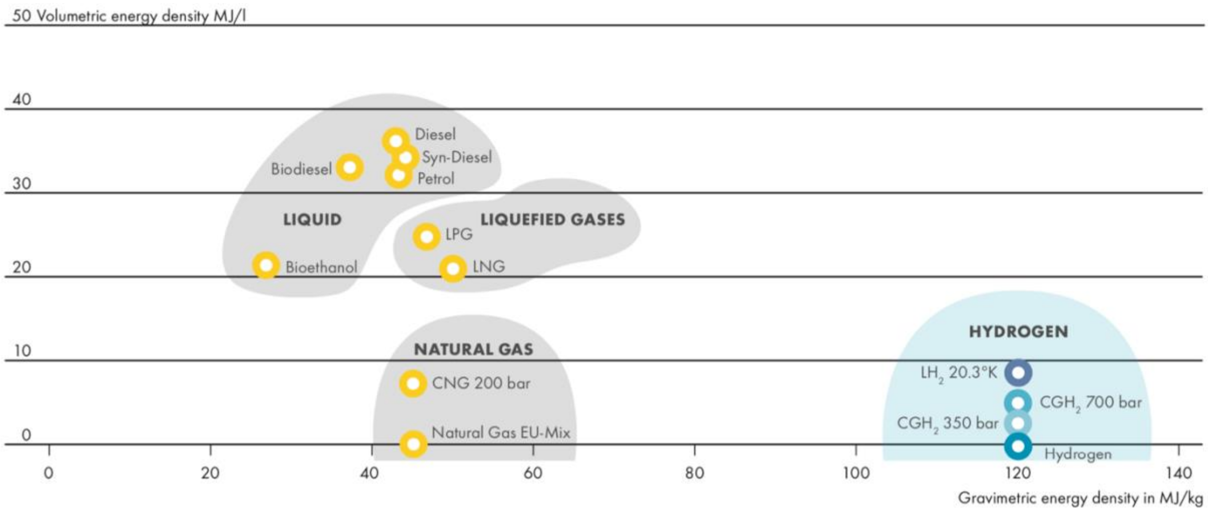


Fig. 11 Energy density of fuels (source: Shell hydrogen study, 2017)

Energy (2017), hydrogen has a gravimetric energy density that is even higher than the one of diesel, by a factor of 3, as can be seen from figure 11. As estimated by the IEA (2017), the energy density of hydrogen is about six times higher in volume and 300 times higher in weight than electric batteries (at least the commercially available technology). Still, due to the very low density of hydrogen, and so its volumetric energy density, hydrogen storage still needs four times more space to achieve the same range of conventional diesel technology (IEA, 2015). Another great advantage comes from the fact that hydrogen is a very flexible energy carrier and it can be generated from many different primary sources, as can be seen from figure 12. Steam

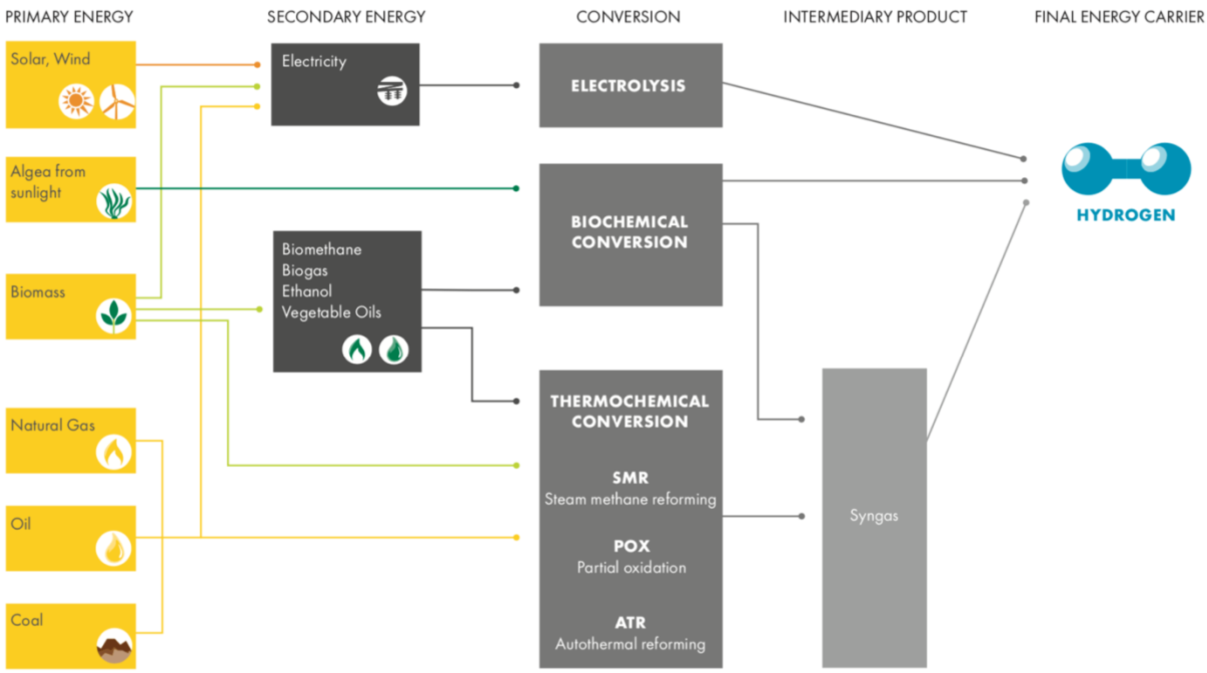


Fig. 12 Hydrogen production processes (source: Shell hydrogen study, 2017)

methane reforming of natural gas accounts for about half of the hydrogen production, according to Decourt et al. (2014). Instead, electrolysis is the most promising pathway for production of low-carbon hydrogen, as it requires electricity as primary energy source. As discussed for PtX applications in the previous chapter, thanks to this characteristic, electrolysis could be used to storage surplus electricity from variable energy generation. Lastly, the use of carbon capture and storage (CCS) also provides an alternative way alternative to generate hydrogen with low life cycle GHG emissions. The pioneer in the research of hydrogen applications and the production of it from electrolysis is Shell, whose preliminary researches started in the 90s and allowed the firm to already make available hydrogen filling stations in California, UK and Germany. California is the key market for development of hydrogen fuel cell vehicles thanks to state's investments to guarantee 100 stations by 2020 and many funding programs (IEA, 2017). For such reasons, the commercially available hydrogen fuel cell powered cars already produced by Hyunday (NEXO), Honda (Clarity) and Toyota (Mirai) mainly target this market. Furthermore, there are demonstration projects of light commercial vehicles, as well as MDVs and HDVs (out of the more than 500 demonstration projects in total), such as those of Scania (2016), Toyota (2017) and UPS, which launched the world's first fuel cell electric delivery truck in 2017. Lastly, a very interesting project has been carried out by the "Société du Taxi Electrique Parisien", consisting of a fleet of 100 hydrogen fuel cell powered taxis. The project, called "Hype", has the objective to raise this number to 600 by 2020.

As for all alternative fuels, a key barrier for the adoption is the refuelling infrastructure. In this case, the costs of building a hydrogen refuelling station and all the components needed for storing hydrogen, being it compressed in its gaseous form, or kept at very low temperature and relatively high pressures in its liquid form, are very high. As estimated by Baronas and Achetlik (2017), the total cost of the engineering, construction and general overhead costs for a station with the capacity to deliver 130 kg to 350 kg per day of hydrogen fall in the range of USD 2.4 million to USD 3.2 million. Additionally, the production costs are very high, even considering centralized applications of natural gas reforming and electrolysis, falling in the range of 2-6 €/kg according to the Shell Hydrogen Study (2017). It has to be pointed out that centralized production plants allow to reduce production costs thank to economy of scale effects, although they increase the cost of transportation and distribution (key player for this fuel) and so may cancel out the reduction of tailpipe GHG emissions reduction. Additionally, the cost of the fuel cell system and the storage tank (which is expected to fall at a much slower pace compared to the other components) is very high. On average, the IEA (2017) estimated the final price of a 260kW truck (with an estimated range of 700 km) is, even in the most optimistic scenario (which considers a series of cost reductions) is more than double of a conventional diesel truck.

This technology seems really promising for commercial vehicles applications, thanks to the high energy density that sets no limits to the weight and range of the vehicle. The possibility of refuelling the vehicle in short timeframes, in the range of 3-5 minutes, comparable with liquid fuels, is another incentive to the adoption of such technology. Furthermore, the production of hydrogen from electrolysis using renewable energy sources and CCS could bring very high life cycle GHG emissions reductions thanks to very high WTW indexes. In order to reach widespread adoption, hydrogen commercial vehicles require strong actions from policy makers to reduce the cost of building the infrastructure needed and to promote the shift towards this alternative fuel solution. Some countries already showed a commitment to reach such target: Japan has already more than 80 operating stations, while Germany planned to have up to 400 operating stations by 2023 and China and Korea are aiming together at a common goal of 830 stations by 2025. This has to be followed by cost savings deriving from technology learnings, which are expected in the years to come, and economy of scale effects. To conclude, hydrogen fuel cell vehicles could not only serve as storage for variable renewable energy generation but could also compensate for the increased demand of electricity that would derive from the widespread adoption of electric vehicles. Hydrogen could ease and reduce the need of big investments in nuclear, solar, wind, and renewable energies in general, energy production plants in the preliminary phase of adoption of electric vehicles and later on co-exist a viable alternative for heavy-duty vehicles applications.

4.5 Alternative fuels – Electric vehicles and batteries

Electric light-commercial vehicles are, out of the alternative fuel freight vehicles commercially available, the most promising technology. Even though the price and range of batteries are still a barrier for long-distance application such as HDVs, their sales are growing at a very fast-pace, boosted by cost reductions, thanks to technological advancements, and policy incentives (in many different forms as seen before). In 2018, PEVs (Plug-In Electric Vehicles) sales passed the 2 million threshold, with an average annual growth rate, or CAGR (compound annual growth rate), of 61% according to the historical data of the IEA. The search of Mehta et al. (2019) estimated that, without taking into account additional cost reductions and widespread adoption patterns, the EV sales volume will reach 5 million vehicles by 2020 and 25 million by 2025. This number is expected to increase taking into account the drastic changes in the battery market for electric trucks and vehicles in general. Compared to 2010 prices have come down by around a factor of four, and densities have more than doubled (Earl et al., 2018). This means that, compared to the first demonstration projects and niche applications of EVs, batteries are cheap enough to be considered as viable for powering trucks. This led to, and at the same time was driven by, a rapid increase in both passenger electric vehicles, electric urban buses and, in a smaller part, light commercial vehicles. For the latter market, 2018 has been a crucial year, with the introduction of many models such as Mercedes eVito and eSprinter, Nissan e-NV200 2018 and the Renault Master ZE. These trends have been boosted by the actions of three different parties:

- Manufacturers, which understood the potential of economies of scale triggered by a heavier adoption of electric passenger cars and started investing in the research and development, both to prepare for the future market needs and to ensure meeting the GHG emission standards. In fact, the list of the commercially available electric LCVs and MDVs is much longer and a portrait of the market as of 2018 can be found in Exhibit 10.
- Policy makers, which have been enacting stringent regulations, in the form of tax incentives, tolls, grants and exceptions to incentivize the adoption of zero emission vehicles. A great example in this sense is Norway, as already cited many times in the regulations' framework chapter, where the total cost of ownership (TCO) of e-LCVs is already lower than that for a diesel vehicle mainly because of its favourable taxation system (Yan S., 2018).
- Courier and logistic services companies, that predicted the importance of adopting sustainable transportation vehicles and invested in the development of demonstration e-LCVs and e-MDVs projects. A list of such projects can be found in exhibit 11, where can be seen how UPS has been one of the pioneers in the research and development of LCVs for urban delivery applications. Another firm that deserves to be mentioned is DHL, which in 2013, in the absence of a manufacturer able to produce an environmentally friendly vehicle for last mile delivery meeting their requirements, strategically acquired StreetScooter, a start-up manufacturing commercial electric vehicles. Today, the production capacity of such vehicles is expected to reach 20,000 annual units, which will eventually replace DHL's entire petrol and diesel fleet. Furthermore, smaller delivery firms and local authorities in the UK, have shown interest in acquiring such vehicles, encouraging DHL to partner with Ford to both increase the current production of 200-km range vans and develop fuel-cell powered vans with an expected range of 500 km (Mehta et al., 2019).

The first applications of battery electric trucks (BETs) dates back to 2008, when in preparation for the Beijing Olympic, 3000 garbage trucks were replaced with battery electric variants to reduce noise and pollution (Moultak et al., 2017). These vehicles are ideal candidates for electrification owing to their predictable routes and stop-start operation (which is where internal combustion engines, ICEs, are particularly inefficient and noisy). China has also been the pioneer in the electrification of the urban bus fleets of its biggest cities. Shenzhen has been at the forefront of this group, where the entire fleet of over 16 000 buses was electrified with batteries. The producer of such vehicles, BYD, is one of the leading companies in the alternative fuel vehicles market, with a company mission of building a sustainable ecosystem similar to Tesla's one. Moving to the European market, the two main players are France and Germany, constituting about 65% of the overall fleet with more 50,000 electric LCVs in 2018 (Mehta et al., 2019). In addition to the LCVs applications described up to this point, there have also been interesting and promising demonstration projects in the HDV market. In the EU market, series production has been announced by MAN, Volvo, Mercedes and others, while Tesla will release in the US its long-range Semi in 2019. As it has been introduced before, California has always been the pioneer of the US market, being the leader also in the medium- and heavy-duty trucks deployment phase. The California Air Resources Board (CARB) introduced a project providing monetary incentives for truck manufacturers to develop zero-emissions and hybrid trucks (IEA, 2017). BYD has been one of the manufacturing partners of the CARB in a pilot project of 11 electric trucks in the San Francisco port. In Europe, Green Freight Europe (GFE) is a leading industry driven program to support companies in improving the environmental performances of freight transport, partially funded by the EU itself. They have been in charge of setting up and monitor logistics data of 127 electric freight vehicles (GFE, 2017). Another program of the European Commission is FREVUE, which helps cities and companies set up demonstrations for relevant stakeholders and publicly disseminates information. As it was the case of other alternative fuels, one of the main barriers to adoption for freight vehicles is the charging infrastructure.

While for LCVs urban applications governments and local policy makers have been investing in charging stations (as seen in the introduction), charging HDVs is a much more complicated matter. Due to the low energy densities of batteries currently available, the trade-off between range needed and cost and weight of the batteries is much more complicated for heavy-duty vehicles. In fact, a key challenge for this application is how to reduce battery needs, either by finding the solution that reduces the size of the diesel engine to the minimum (for hybrid vehicles) or through the supply of electricity to vehicle while in motion. This solution, which is called "electric road systems" (ERS) rely on the installation of the charging infrastructure along the road upon which the vehicles drive. This can be done in two different ways: overhead catenary lines or inductive transfer of power. The latter solution requires the installation of coils in the road generating an electromagnetic field transferring electricity through similar coils installed on the vehicle. Overhead catenary lines require instead the vehicle to be equipped with a retractable pantograph. Even though inductive charging provides many advantages, including no limitations on the number of vehicles that can be charged (allowing to eventually use the same solution for cars and share the costs with a broader vehicles base) and lower maintenance costs, it has a lower efficiency and much higher installation costs, since it's a more invasive solution (IEA 2017). For such reason the pilot demonstration projects of in-motion charging infrastructures are almost exclusively dedicated to overhead catenary lines. The main investor in this field is Siemens, which recently embarked in 3 demonstration projects in Berlin (2 km test track), Stockholm (2 km highway) and in the Long Beach port of Los Angeles (IEA, 2017).

Leaving the analysis of costs of batteries, charging stations and infrastructure, for both customers and manufacturers, to the next section, the GHG emissions reduction potential of this technology must be assessed in its entirety. Even though Battery-electric vehicles by definition emit no local pollutants at the tailpipe, upstream emissions could eventually outclass this achievement. Furthermore, the GHG emissions reduction of hybrid vehicles will also depend on share of electric driving versus the use of fuel from the ICE, in addition to the carbon content of the resource used to produce the electricity that charged the batteries. Hence, as with biofuels and hydrogen, the contribution of electricity as an energy carrier to the decarbonization of the road freight sector is dependent on the decarbonization of the fuel supply chain. Still, taking into account the trends expected in renewable energy production plants construction and the targets of decarbonization to be met by countries around the world, electric trucks are the technology expected to bring the highest GHG emissions reduction in the next 20 to 30 years. The results of the research conducted by Moultak et al. (2017) shown in figure 13 clearly justify the latter statement, comparing the WTW GHG emissions in CO_2 equivalents and per km

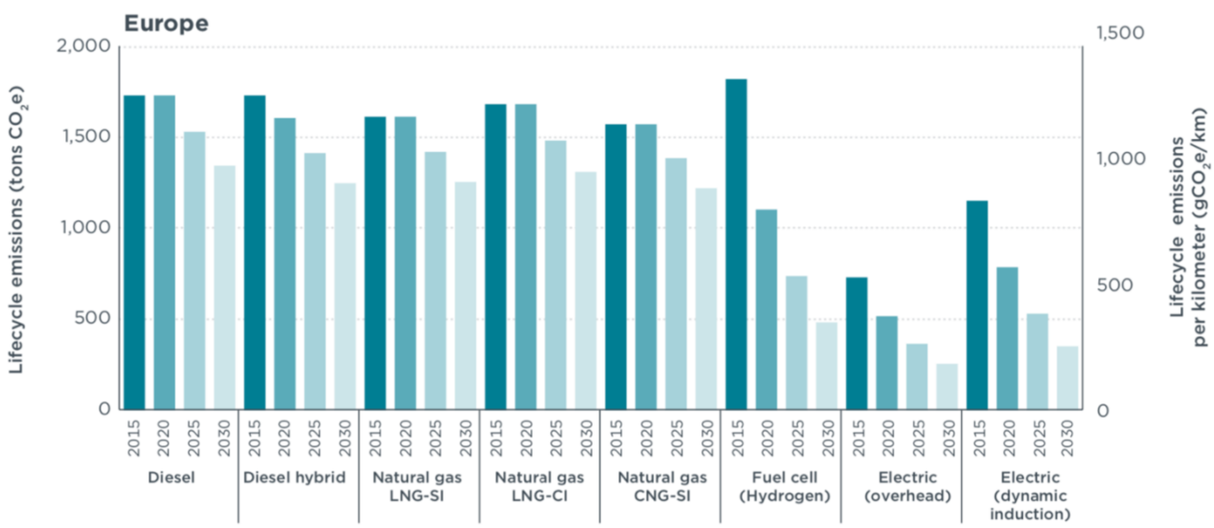


Fig. 13 EU lifecycle CO_2 emissions by technology type (source: Moultak et al., 2017)

Fuel	Region	Fuel carbon intensity (gCO_2e/MJ) 2015	Fuel carbon intensity (gCO_2e/MJ) 2030	Greenhouse gas emission reduction in 2030*
Diesel	All	102	102	-
Compressed natural gas	All	81	81	-
Liquefied natural gas	All	86	86	-
Hydrogen	All	151	70	54%
Electricity	United States	144	49	66%
	Europe	101	44	57%
	China	202	82	60%

**Greenhouse gas emission reduction includes on-vehicle efficiency improvement (i.e., relative MJ per kilometer)*

Fig. 14 Fuel carbon intensities (gCO2e/MJ) and GHG emissions reduction expected (source: Moultak et al., 2017)

driven. The analysis of lifecycle emission was performed assuming the carbon intensities shown in figure 14. Although the aforementioned paper does not include biofuels in the scope of the analysis, the graph is able to show the potential of each technology elicited in this research. Overhead catenary applications are expected to reach lower GHG emissions thanks to smaller interventions needed to install the infrastructure on the road, while inductive charging methods are expected to pollute more during this adoption phase. It has to pointed out that, due to lower maintenance needed, once the electromagnetic coils are installed under the road surface, dynamic induction could generate higher long-term emissions reduction. In the proposed graph, only the European situation is shown, while in the reference paper also the results for China and the US can be found. This choice is justified by the fact that, thanks to a higher share of renewable energies in the energy mix of European countries, the expected lifecycle emissions of electric vehicles are the lowest, showing the true potential deriving form a sustainable grid. A similar analysis will be done, in the following chapter, for the costs of adoption of each technology.

Technology advancements have already reduced dramatically the costs in the last decade, particularly of batteries, as it will be shown in the next chapter. Even more, car and freight vehicles manufacturers have understood the importance of investing in research and development of electric solutions for the future. The Statista report (2019) mentioned before gathered all the strategic plans and launch of new vehicles in the entire automotive industry, including new players expected to enter the electric vehicles market, highlighting a very strong message from the manufacturers side. Additionally, every day new startups are coming up with disruptive ideas and innovations that could introduce even more alternatives than those already studied and tested. For all these reasons, policy makers will be the key enablers in the widespread adoption of electric freight vehicles, even more than in the last decade. They can play a number of different roles, from introducing standardized charging protocols (as they did for hydrogen), provide funding streams for R&D of batteries and other components, as well as funding demonstration projects up to enacting conventional incentives and regulatory frameworks. For example, income from tolls for low-emission zones could be reused as funding for R&D projects, creating an example of circular economy that could speed up the adoption of such vehicles.

Finally, as highlighted in the professional survey performed by the ITF in 2018 (previously mentioned in this paper), companies and professionals themselves agree on the potential of electric LCVs. In particular, almost 50% of the respondents believe that full battery electric vehicles are the best solution for urban delivery, with the second most promising technology being hybrid, with a consensus that is more than 20 points below. This belief was found also when the professionals were asked to answer when the various alternative fuel technologies will reach widespread adoption in their opinion. As a matter of fact, around 50% of the respondents agreed that both hybrid electric and full-battery electric vehicles will reach the aforementioned stage in the 2020-30 timeframe. It will be shown in the next chapter, and in the conclusion, as there are already applications that have reached cost parity. Although these represent specific applications, many papers and researches agree that, before 2030, widespread adoption of electric commercial vehicles will be reached, and before 2050 this result should be achieved also for heavier trucks.

5 COMMERCIAL BEV TOTAL COST OF OWNERSHIP

5.1 Scope of the analysis

The objective of this chapter is to analyse economic figures and trends of the costs and benefits of the adoption of electric LCVs in comparison with conventional ICE commercial vehicles. Light commercial vehicles were chosen because of less stringent business requirements in terms of range needed and potentially shorter payback periods given the size of the fleets that would share the upfront investment costs. Furthermore, LCVs represent the second biggest category of electric vehicles after passenger cars, representing almost 10% of the electric vehicles on the road, with 250,000 e-LCV circulating in 2017 (IEA, 2018). This number shows how subsidies and tax reductions (or additional taxes charged for ICE vehicles) are incentivising the adoption of electric vehicles also on the commercial side. The largest electric LCV fleet is in China (170 000 vehicles), followed by France (33 000 vehicles) and Germany (11 000 vehicles) according to the data gathered by IEA (2018). As discussed with Iveco engineers an ideal business case would be urban logistics vehicles with a gross weight up to 7.5 tons, definition slightly different from the one given in the classification chapter, in order to include cases of higher GVW still falling in the urban delivery case. In fact, this definition is much more related to the business application of electric last-mile vehicles rather than focused on the regulatory classification of vehicle categories according to GVW. Furthermore, the weight of the battery pack becomes less important with the increase of the gross vehicle weight, justifying even more the choice of the aforementioned mission. Urban logistics includes a series of activities: mail delivery, courier delivery trucks (DHL, UPS, etc.), last-mile delivery of goods (distribution in the retailing industry, supermarket chains, etc.) and online retailers such as Amazon (even though in this case the trend of delivery drones should be taken into consideration). For such activities, it was estimated that the delivery vehicle will need a range of 50-70 km to allow the accomplishment of daily tasks. The indicated range can be achieved with batteries at the current state of the art technology, commercially available, which do not require high additional costs, or that can be compensated by incentives and operational costs reductions in the very short-term. The advantage of having a battery range correspondent to the daily need is related with the possibility of charging the vehicle during the night, avoiding the logistics company to rely on the installation of public charging stations. In fact, from a business point of view, evidences have been found on the reluctance of urban delivery companies to stop the vehicle on the road for charging (even if for short times in the range of 30-60 minutes).

An alternative which is being discussed for urban applications is battery swapping, in which the electric vehicle can exchange its depleted battery for a fully charged one. The depleted batteries are recharged at the station and hereafter used for other electric vehicles with depleted batteries. The business model proposed by Better Place in California consisted of a network of battery swapping stations and the batteries were owned by the company itself and leased from the recharging service provider. In fact, this model would allow the owner to lease additional batteries in case he or she needed to do a longer trip, while leasing a smaller battery for urban activities, hence reducing the upfront capital cost. This concept is also argued to reduce the time it takes to recharge an electric vehicle from a couple of hours to a few minutes (den Boer et al., 2013). If this concept would be applied to electric trucks, it would make the recharging time competitive with the time it takes to refuel a conventional diesel vehicle, eliminating an important barrier to the uptake of electric trucks (den Boer et al., 2013). Unfortunately, this model also has a series of limitations, such as the expensive network of swapping stations, the risk of overcharging the electricity grid in case the entire stock of batteries needs to be charged at the same time, and more importantly, batteries need to be standardised in order to allow the swapping process to be automatized. Better Place had a partnership only with Renault, which limited a lot their possibilities and even today, the standardisation of batteries would be very complicated, if not impossible, to be achieved. As a matter of fact, even though they had a partnership with governments and airports (such as Schiphol in Amsterdam) for the application of this concept to the charging of their bus fleet, Better Place went bankrupt early in 2013 (den Boer et al., 2013). Alternatively, the battery swapping station could be installed inside the warehouse facility of the logistics services provider and the batteries could be charged while the vehicle is conducting its operations and then, during the vehicle filling at the warehouse, the drained battery pack would be replaced with a new charged one. In this case, the battery swapping technology introduces higher flexibility thanks to the fact that logistics operations could be performed during the night, with the advantages shown in the previous chapters and at the same time it reduces the risks of electricity grid defaults affecting the firm’s activity thanks to a stock of charged batteries (they could cover the maintenance time needed to fix the network). Nevertheless, this solution wouldn’t take advantage of the lower price of electricity during the night, unless the company would actually be able to conduct its activities during the night, and even in that case the company would incur in higher personnel costs (higher wages for night shifts). This solution requires a number of battery packs which is higher than the number of vehicles, therefore it implies higher investment costs. As a consequence of that, the higher upfront investment cost, in addition to the uncertainty in real operating costs, could make this solution not competitive for this application. In fact, it seems much more interesting for public transportation applications (buses, tuk-tuks, etc.), rather than for LCVs, thanks to a higher predictability of the running times and annual mileage, lower operating costs (public electricity) and operations already occurring, in part, during the night.

Moving back to the previous solution, the installation of charging stations at the company's warehouses introduces an additional cost for the final user, which must be carefully considered in the definition of the total cost of ownership (TCO). At this preliminary phase, it still seems to be an interesting solution thanks to the possibility of ensuring business continuity during the day, guaranteeing sufficient power to charge all the fleet (allocated as to reduce the number of charging stations to the minimum and limit the investment) and attracting additional incentives from policy makers. There is a real practice case that confirms this choice and has been developed by UPS[6]. The United Parcel Service (UPS) company is largest logistics services firm in the world (considering the entire group of subsidiaries) in terms of revenues and one of the pioneers in sustainable transportation in the industry (as seen in the previous chapter). The aforementioned project, called Smart Electric Urban Logistics (SEUL), was launched in April 2017 and will be completed in September 2019, as part of five-year strategy for the electrification of UPS's entire central London fleet of 170 vehicles[7]. The collaboration with the UK Power Networks company will allow UPS to increase the number of electric vehicles from the previous 65 LCVs (from now on this term will consider vehicles with a GVW up to 7.5 tons) to the aforementioned target without the need reinforce the local electricity network. Charging simultaneously a big number of trucks' batteries puts significant demand on the depot's electricity supply. The proposed smart grid system will allow to continuously control the demand of electricity of UPS' depot to avoid reaching the networks' limit, even in the case of peak demand thanks to a battery storage installed on site. Thanks to this solution, UPS will be able to fully convert to electric LCVs, while avoiding significant investment in network electric infrastructure.

[6] Case briefing available at: https://www.ukpowernetworksservices.co.uk/case-studies/ups-smart-electric-urban-logistics-project
[7] From the UK Research and Innovation article available at: https://gtr.ukri.org/projects?ref=103254

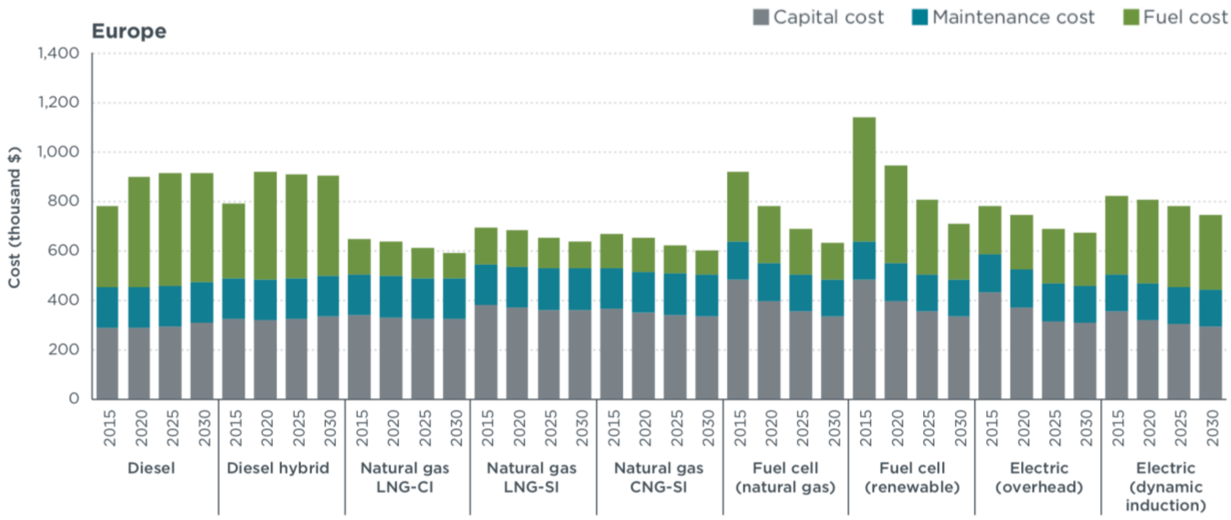


Fig. 15 Cost of ownership for different long-haul heavy-duty truck technologies (source: Moultak et al., 2017)

Real practice applications and the commercial availability of cost-effective components are the reason why electric vehicles were chosen for the scope of the economic analysis. An estimate of the TCO costs obtained in previous works is shown in figure 15. Even though the work of Moultak et al. (2017) was dedicated to heavy duty applications, which have much higher operating costs, the higher capital cost ensures a similar cost structure to LCVs. In fact, the proportions in the comparison between different fuel technologies should remain relevant for the case that will be analysed in the next section. Although predictions for the future years are subject to big fluctuations, due to the variety of factors that influence the cost-effectiveness of such technologies in the long-term, electric HDVs are expected to reduce the TCO compared to conventional diesel vehicles already in the next decade. It will be shown how, thanks to technology advancements and incentives are already competitive today.

Last but not least, LCVs (and part of MDVs due to the new definition for the purpose of this chapter) were chosen because of their impact in terms of GHG emissions. Even though heavy-duty vehicles are the most pollutant category in absolute terms, due to their higher annual mileage and fuel consumption, they are a much more efficient category in terms of energy density. This physical dimension takes into account the energy consumption in terms of liters of diesel equivalent (lde) per ton of payload and per km driven (tkm). As can be seen in figure 16, LCVs and MDVs are in fact the least efficient categories, which is why the analysis will focus on the “hybrid” category of urban delivery truck up to 7.5 tons. Assessing the GHG emissions of this category and providing a cost-effective application would be a potential solution, in addition to the complete transition towards electric passenger cars, to the problem

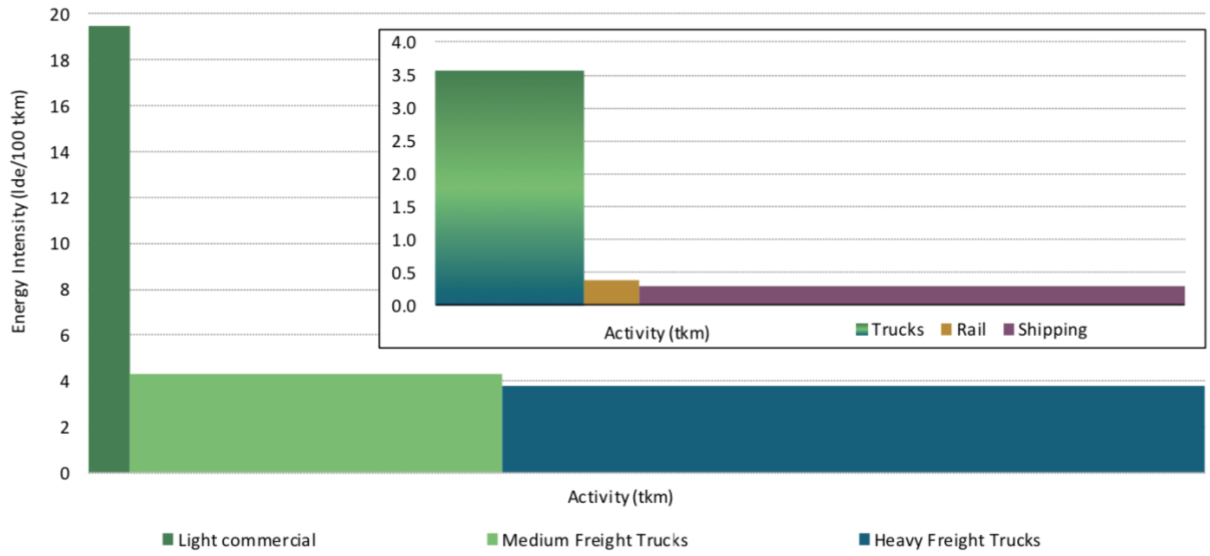


Fig. 16 Global stock average freight energy intensity and activity in 2015 (source: IEA, 2017)

of high concentration of CO_2 in urban areas. The analysis will be limited to applications in the European continent due to the higher availability of data and more homogenous driving patterns (for example annual mileage, due to different size of urban areas). The latter condition ensures more realistic and precise data on the operational costs and provides a scenario that can be used as benchmark for many different countries.

In the following section, the costs deriving from the adoption of electric vehicles will be analysed and compared with conventional ICE LCVs. Each component of the TCO will be analysed separately, using the available data, and, where possible, projections will be made for the next years. As introduced before, the objective of this chapter is understanding if and when electric light vehicles will be competitive and cost-effective for the widespread adoption of urban logistics companies.

5.2 Total cost of ownership

The total cost of ownership (TCO), is a key parameter in commercial applications, since the costs that the owner will incur along the life of the vehicle will directly impact the operating costs of the firm, hence the margin. Being able to cut costs and improving the efficiency of daily operations are the main levers for logistic services companies, due to high levels of competitions and very low opportunities of differentiation. In fact, the introduction of electric vehicles could drive down dramatically operating costs, in particular "fuel" costs and maintenance, thanks to a lower number of parts in the drivetrain (as will be seen later). Furthermore, urban and regional logistics companies, heavily relying on LCVs, and sometimes MDVs, are usually the owners of the vehicle's fleet (differently from HDVs and international expeditions companies). For such reason, this section aims at analysing if and when the benefits in terms of cost reductions over the life of the vehicle are able to fully compensate the additional cost of electric vehicles, without taking in consideration, for the moment, the contribution of incentives and tax reductions. The latter will play a very important role in the end of this section when comparing the TCO of an electric LCV with the one of a conventional ICE vehicle (ICEV). Before doing so, all the components of the total cost of ownership will be analysed separately, including the expected trends of the costs of some components. It has to be said that one of the advantages of an electric LCV is that many of its components are shared with electric cars. This means that many costs can be derived from the extensive research done on electric passenger vehicles, and most importantly, the technology advancements of the latter industry will contribute to the reduction of the costs of the electric LCVs as well. The TCO breakdown, in general, is done in five components: vehicle, taxes, fuel/electricity, maintenance and replacement of some components. Taxes include all those paid during the life of the vehicle, rather than being limited to the ones paid during the acquisition, ranging from registration up to circulation taxes. Replacement will not be considered in this paper for simplicity, since there is a high degree of uncertainty on the real duration of the batteries and other vehicle components, also due to the fact that they depend on a variety of factor and usage behaviours. On average, it was estimated that the lifetime of an electric vehicle is in the range of 8-10 years, while conventional ICEVs have an expected lifetime of 11 years. Due to the uncertainty and the very small gap between the two values, it seemed reasonable to assume that this factor will not play a role in the electric vehicle adoption in the next years. In addition to the aforementioned components, this case requires also the analysis of the cost of the charging infrastructure that will be owned by the logistics services provider.

Starting from the electric vehicle costs, it is necessary to make a big distinction between the battery and other components costs. In fact, as shown by Fries et al. (2017) in figure 17, batteries account for almost half of the total manufacturing costs of an electric vehicle. The absence of an engine and an overall smaller number of parts, allow the vehicle, excluding the battery, to be much cheaper than an ICEV. For such reason, the battery technology and costs will be the first one to be analysed. The battery technology used in the majority of vehicles is based on the Lithium-ion technology, which is traditionally composed by a lithium-based cathode and a

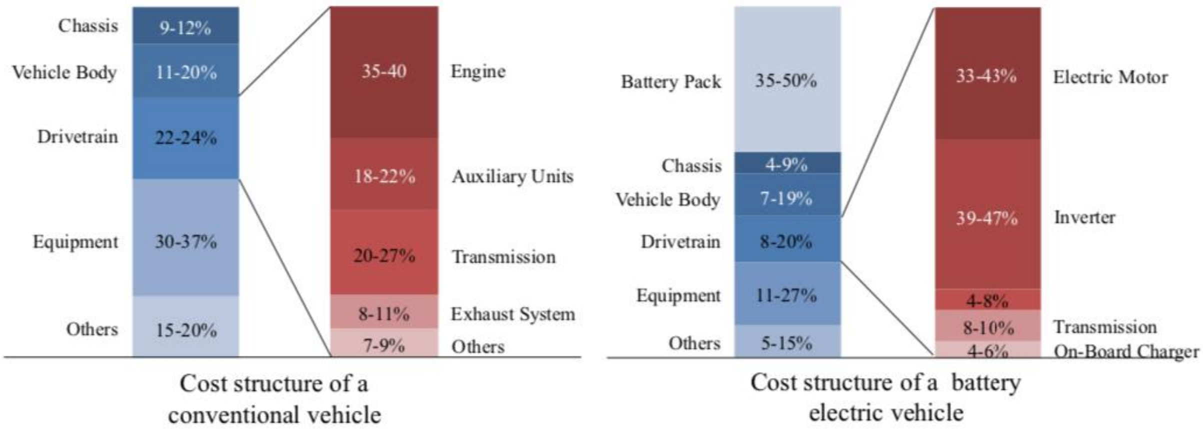


Fig. 17 Vehicle costs breakdown (source: Fries et al., 2017)

graphite anode. These will form a single battery cell which are then assembled, in a combination that depends on the final capacity needed for the vehicle range to be achieved, with other components to form the battery pack. Recently, there have been proposed modifications of this chemistry, in particular, solid batteries (relying on silicone), lithium-air and lithium-sulhpur batteries are expected to reach really high energy densities and bring down the cost per kWh. Before showing potential breakthroughs and trend of the future, it has to be said that the cost of batteries has heavily reduced in the last decade. Thanks to economies of scale and technology advancements, the cost of batteries fell by a factor between 4 and 10, compared to the 1000 USD/kWh of 2010 (IEA, 2018). There is a lot of uncertainty concerning the current cost reached by batteries, ranging from 350 USD/kWh, up to 100 €/kWh, depending on the research paper. According to experts' opinion, the upper bound aforementioned is way too high considering the data made available by producers of such component. This value, which strongly depends on the volume of production, has been decreasing thanks to the investments in the creation of very big production sites around the world. Tesla has been one of the key players, by building the Gigafactory, in collaboration with Panasonic, inaugurated in July 2016 and started the mass production of battery cells in 2017. This factory, which claims a record production of 35 GWh/year of cells, is expected to bring the battery price below the 100 USD/kWh, which would allow the introduction of cost-effective battery electric HDVs, such as the Tesla Semi Truck (IEA, 2018). Another key player in this field is LG Chem, a pioneer in the production of electric battery packs for the automotive industry, starting the first production of lithium-ion batteries in 1999 and becoming the leader of the market in 2011[8]. Today they are the supplier of Ford, Chevrolet and Renault for their battery electric vehicles and they announced they will also

[8] https://en.wikipedia.org/wiki/LG_Chem#Energy_solutions

supply Volvo for the next models. Overall, there have been many announced plants for the next years, including very recently Volkswagen for the I.D. series, some of which are shown in the table in exhibit 12.

Furthermore, technology advancements are expected to increase also the battery energy density, which already doubled during the last decade. This factor, expressed in kWh/kg or kWh/lt, is a very important element in particular for commercial applications. Higher energy density means batteries cost less, weigh less, and last longer, promising electric vehicles without the sticker shock or range anxiety. In 2010, the start-up 24M was launched by three MIT engineers, thanks to a successful round of funding from venture capitalists. They claim to deliver cheaper and better batteries, using a "semisolid" lithium-ion technology, which would be able to achieve much higher energy densities. Although there isn't yet a commercially available product, only test versions of the aforementioned battery, their lab-scale version has an energy density of around 300 Wh/kg according to Temple (2018), which exceed the current leading technology with 250 Wh/kg. The group even demonstrated that this battery would be able to reach 350 Wh/kg and at the same time they are developing another Li-ion battery able to get very close to energy densities of 500 Wh/kg (Temple, 2018). This is to say that, if they will reach the goal of delivering the first products to the market, thanks to an industrial partner and additional funding for scale production (including from the electronics giant Kyocera Group), things will change in the battery market, with prices falling down even faster than expected and an increased competition which will bring more frequent technology advancements. Although this and other projects are still at an experimental phase, they justify the trends expected for the price of battery packs in the next decade.

There have been many researches and publications in recent years about the trends expected for the battery price in the next two decades. In addition to these technology reviews, car manufacturers and battery producers have announced innovation breakthroughs and new production plants, which consequently caused updates to the aforementioned trend predictions. A recent research of Lutsey & Nicholas (2019) gathered such predictions to perform a comparison of both the current battery costs and the ones expected in the 2020-2030 timeframe. The result of this paper is shown in figure 18 and will be used as a reference in the determination of the average battery pack cost for the calculation of the TCO of the case introduced in the scope section. Apart of Tesla, which is slightly below average in terms of battery pack costs, the other technical analysis' outcomes and producer announcements are in the range of 170-

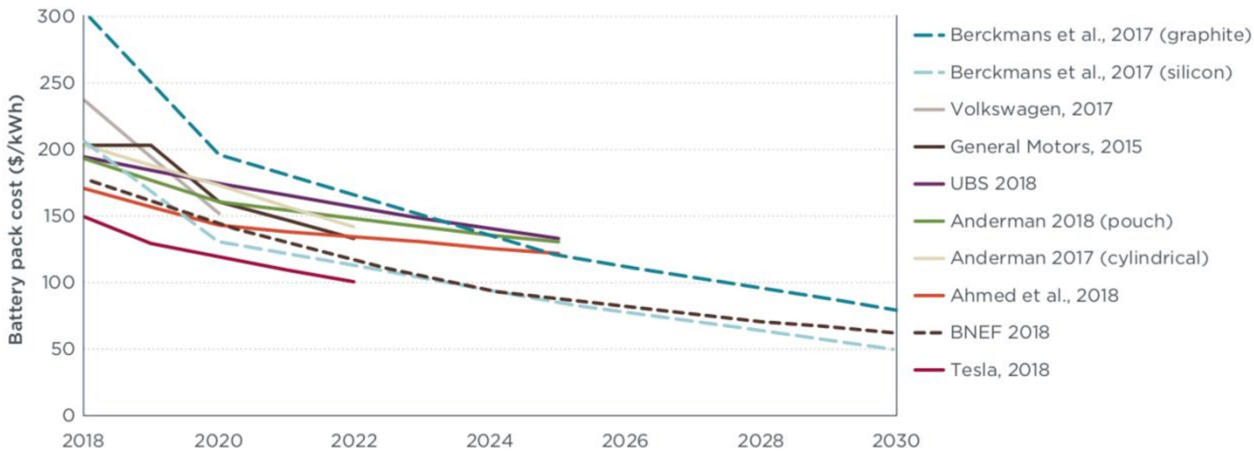


Fig. 18 Electric vehicle battery pack costs from technical studies and automaker statements (source: Lutsey & Nicholas, 2019)

200 USD/kWh, which would correspond to 150-180 €/kWh considering a euro-dollar exchange rate of 1,12 USD/€. The average industry battery pack cost (more interesting than battery cell cost for the purposes of the thesis) deriving from this research is 176 USD/kWh, which corresponds to 157 €/kWh. This value was calculated taking into consideration the cost of a typical 50 kWh battery, which is not so far, as will be seen later, from the average battery size of commercially available electric LCVs. For such reason, it seemed a reasonable estimate of the current state of the art technology and will be used as baseline for the calculation of the TCO.

Moreover, it has to be pointed out that many of these researches have been conducted for the passenger car market, although the scope shouldn't have an impact on the final battery cost per unit of energy stored. In that case, due to the smaller power of the electric motor needed, which is directly correlated with the GVW, the battery size tends to be smaller. As it was proven in the research of the IEA (2018), the correlation between the battery size and its cost is not linear. Large batteries tend to have lower specific costs because of two great scale advantages: large batteries have higher cell to pack ratios (consequently higher energy density), and the cost of the battery management and cooling systems is spread across a larger energy capacity, reducing their incidence in the cost per unit of energy stored. This would be a great advantage for commercial fleets, in particular for MDVs used for regional deliveries, which need larger batteries due to both higher GVW and longer range required. The effect of these phenomena on the final cost of the battery is shown in exhibit 13, both for the size and scale effect.

A second aspect that has to be considered for the battery is the charging method, since it's speed and charge management directly influences the lifetime of the battery. In recent years, major developments in the field of charging methods have followed the technology advancements of the battery technology. In particular, when talking about commercial application the possibility of using superchargers need to be introduced. In fact, this technology would allow very short charging times, about 40-60 minutes to reach a level of charge of 80%, which could decrease the performance gap of EVs compared to ICE vehicles, particularly for LCVs and buses applications. On the other hand, even though such speed does not constitute a challenge for the current battery design, increasing the maximum speed above the current limits may shorten the lifetime of the battery. For such reason, overnight charge was proposed in the scope section, since it would take advantage of idle times in the operations of the logistics company, while avoiding the need to implement ultra-fast charging (300-400 kW) that could be very dangerous for the battery itself (IEA, 2018). Another important element to consider is the state-of-charge (SoC) of the battery, or it's complementary depth-of-discharge (DoD), and it has to be managed very carefully to avoid reducing the lifetime of the battery cause by improper use. In order to avoid an excessive shortening of the battery life, batteries must never be fully discharged, particularly for BEVs applications, while for PHEVs the SoC is not so important since the battery is charged and discharged much more frequently due to smaller size of the battery pack and consequently lower risk of full discharge. At the same time, to avoid increasing too much the temperature of the battery and posing a fire hazard, the battery shouldn't be over-charged (Dalla Chiara et al., 2014). As a consequence, batteries usually have protection circuits that constantly monitor their SoC and the resulting usable energy capacity, which is the portion of the energy stored that can actually ne used by the vehicle, is around 80-90% of the nominal one. As a matter of fact, Tesla's superchargers usually slow down the speed of charge when getting closer to 80% of charge levels and the car's board computer stops the charging before reaching full charge. These practices allow EV batteries to withstand, on average, 1,000 cycle degradation according to IEA (2018). This means that, considering a battery capacity of 35 kWh and average consumptions of 0.2 kWh/km, the life cycle threshold would not be reached before 175,000 km of driving for passenger cars (IEA, 2018). Considering that for LCVs the battery size is on average double the aforementioned, and that, as will be seen later, a commercial vehicle usually consumes 0.4-0.45 kWh/km in urban/regional trips, the same value would be obtained for a commercial fleet. This is in line with conventional ICE vehicles lifetime and it justifies the assumption that was made when not taking into account the replacement of depleted parts in the calculation of the TCO.

Taking now into consideration the costs of the electric drivetrain, as shown before in figure 17, they are much smaller compared to the cost of the battery pack, on average by a factor of 3-4 depending on the power needed by the vehicle. In fact, the main remaining components of the powertrain have a cost that is normally expressed on a per kW basis. The components costs are derived from the research of Fries et al. (2017), where they are broken down into macro-groups. The first components analysed are part of the electric motor, including the permanent synchronous and asynchronous electric motors and the transmission, with a cost of 23 €/kW in 2017, expected to reach a value of 18 €/kW in 2020. Calculating the compound annual growth rate (CAGR) as:

$$CAGR = \left(\frac{End\ value}{Initial\ value}\right)^{\frac{1}{years}} - 1$$

a reduction in the costs of these parts of 8% per year is obtained. This means that, in 2019, we can expect this module to be priced (although it's not sold separately from the car) at 19.5 €/kW. This value is close also to the electric motor cost forecasted by Stewart & Johnson (2016), which projected this component to reach a cost of €15/kW in 2030, showing that the major price reductions are expected from the battery pack rather than the powertrain. The second group to be analysed is the power electronics, of which the most important and expensive component is the inverter. Using a similar approach to the electric motor, the price of this module is extrapolated calculating the CAGR from the cost in 2017, 4.5 €/kW, and the projected cost in 2020, 3 €/kW, obtaining a value of 3.4 €/kW. The remaining module is composed of all the components which cost does not depend on the nominal power of the vehicle. This group includes the AC-DC converter and the on-board charger (to charge the batteries during the breaking phases) and its cost is fixed, around 700 € (Fries et al., 2017).

The following group of cost is the second most important cost in the comparison with a conventional ICE vehicle, and it's the fuel cost. It is a key parameter since it's responsible for the bigger part of the operating costs reduction in the transition to the adoption of electric LCVs. As a matter of fact, the research of Hensley et al. (2012) was able to analyse the economic competitiveness of electric vehicles, in this case passenger cars, referring all the costs terms of the TCO to the fuel and battery price. Although the outcome is not directly influencing the analysis of this dissertation, it seemed interesting to show how much the fuel price is able to determine whether or not electric or hybrid vehicles are cost-effective. As it can be seen in 2011, even hybrid technologies (non plug-in, such as Toyota cars) were not convenient, while

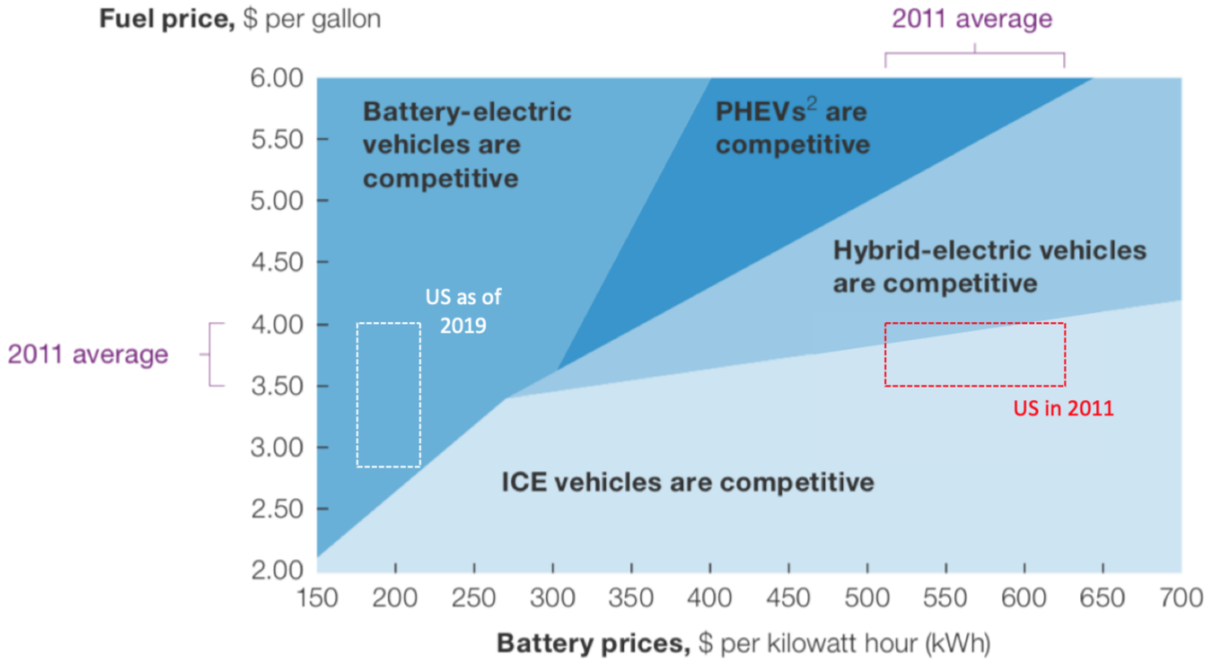


Fig. 19 Electric vehicles projected competitiveness based on TCO (adapted from: Hensley et al., 2012)

in 2019, the situation has drastically changed. Thanks to the higher taxes on fossil fuels in California, determining the upper boundary of the region highlighted in white, and the technology advancements of the battery cells mentioned before, from the point of view of the research BEV would be much more competitive than conventional ICE vehicles. Still, this is the case of passenger cars and the method used in the aforementioned research is not in line with the one adopted here, which is why the results shown in figure 19 are merely qualitative. In general, it can be said that electric vehicles provide fuel efficiencies (in final energy terms) that are two-to-four-times higher than ICE powertrains (IEA, 2018). This result is due to both higher efficiencies of the powertrains, which are in the order of 80-90%, and to the regeneration of kinetic energy when braking, which also brings an additional reduction of the maintenance costs. In fact, both hybrid and electric vehicles are equipped with a kinetic energy recovery system, that converts in electricity the energy that would be otherwise lost as heat by the brakes. This energy is stored in the battery and allow the vehicle to consume a smaller amount of energy, in particular for urban applications in which there is a higher frequency of speed variations. For this reason, electric vehicles are much more efficient in start-and-stop trips in urban areas compared to ICE vehicles. First of all, the cost of charging an electric vehicle will be taken into consideration, which will then be compared with the cost of fossil diesel. This parameter is not so easy to be calculated, due its dependence on when the owner chooses to charge the vehicle and whether public and rapid charge points are used. In fact, overnight charging requires to take in consideration a discount on the average price of electricity reflecting current off-peak tariffs observed in Europe. With continued decarbonisation necessary within the electricity grid, supply volatility is expected to increase with greater penetration of renewables (Stewart & Dodson, 2016). As have been seen recently in Germany, there are moments in which European countries (and in general those with a high share of renewables in the electricity generation mix), experience negative wholesale electricity prices during times of high generation from renewable sources, particularly solar photovoltaic. For such reason, a price discount for overnight charging is even more justified, since suppliers will be interested in incentivising the EV's uptake with cheap off-peak tariffs or managed charging schemes designed specifically for EV owners. As a matter of fact, the load levelling effect, which means increasing the demand during night time, when usually the demand reaches its minimum, would allow suppliers to avoid regulating the power of production of their plants. Their nominal power is designed to withstand the peak demands that normally occur in early morning or evening and any variation requires necessarily a reduction in the efficiency of the plant. For such reason, increasing the demand of electricity overnight would be a great advantage for suppliers, thanks to increased efficiency, lower costs and no need, for the moment, to invest in upgrading the current distribution network. This requires taking into consideration current off-peak tariffs observed in Europe, which can be included in the analysis by applying a 30% discount on the current average electricity price, as considered in Stewart & Dodson (2016). The updated average industrial price of electricity of the EU-28 area, from Eurostat (2018), is 0.1142 €/kWh, calculated as weighted average of national data for consumption by non-household consumers. Applying the aforementioned price discount, a value of 0.0799 €/kWh is obtained, which will be used in this paper for the calculation of the TCO. This value assumes that the urban logistic services providers will charge their vehicles only overnight, by using automated charging systems. Otherwise, if we were to consider also charging during the day, situation in which such companies could still be able, in some cases, to negotiate a lower price to use the additional energy produced by solar plants, the price would be in general much higher and wouldn't bring great advantages over diesel LCVs. Finally, public charging is not considered in this paper due to the variability of prices and data available. In fact, the article of Earl et al. (2018) highlighted how the price of public supercharger covers a range going from €0.55/kWh of the Shell supercharger, down to 0.06 €/kWh promised by Tesla, at least for US customers, with a ten-fold difference, The calculated value needs then to be compared with the cost of diesel of conventional ICE commercial vehicles.

The cost of diesel is of much more uncertain evaluation due to the different excises that governments apply, varying not only from country to country, but also at a national level depending on the vehicle class. As a matter of fact, the paper of Earl et al. (2018), identified that, on average, business customers in the EU paid a sales weighted average of €0.45/litre in excise duty, which considers both the diesel fuel rebate offered in an increasing number of Member States and the business exemption of VAT. In their paper, the final diesel price resulted in 1 €/lt, considering a diesel cost of 0.55 €/lt. This price, is much lower than the price of diesel, extracted from the weekly oil bulletin of the European Commission (2019), of 1.376 €/lt, weighted average in the EU-28 area. Considering the same average excise duty, since it seems a reasonable estimate of the average 20% VAT exemption in the EU area and the diesel fuel rebate offered to companies with a large fleet of industrial vehicles, the current average diesel price can be calculated. Using the same report of the European Commission aforementioned, which is updated on a weekly basis, the average diesel price without taxes is 0.637 €/lt, obtaining a final EU-28 weighted average diesel price for business customers of 1.087 €/lt.

The last parameter to be considered in the fuel costs reductions deriving from the adoption of electric LCVs is the energy consumption of the two different solutions. Concerning the consumption of energy of an electric LCV, the data available is really poor, due the scarce variety of commercially available vehicles. In fact, publications and researches differ a lot in the assumed energy consumption of such vehicles, in particular considering that this parameter depends on the weight of the vehicle, ranging from 0.3 kWh/km for smaller urban vans, up to 0.46 kWh/km for bigger regional MDVs. Considering the GVW range chosen in the scope of this analysis, a conservative assumption would be an average energy consumption of 0.4 kWh/km. On the other side, the data available for conventional diesel vans is much richer, including public available databases such as the UK government vehicle certification[9]. Taking in consideration large vans with a GVW of 5 tons, which is exactly the mean value of the range considered in the scope of the analysis, the obtained average fuel consumption of diesel models is: 30.06 mpg (miles per gallon) for urban cycles and 37.48 for extra-urban ones. In fact, due to less frequent variations of speed, extra-urban trips will tend to consume less fuel. Converting these values in lt/km (using the UK imperial conversion factor) and considering an average use of such vehicles of 80% urban and 20% extra-urban, given that regional use will be limited to trips to reach the urban area from and to the warehouse (usually located outside of towns) and

[9] Available at: https://vanfueldata.vehicle-certification-agency.gov.uk/vehicles.aspx

rare regional operations, the average fuel consumption to be considered in this paper is 11,17 km/lt, or 0,089 lt/km. By multiplying these values for the price of electricity and diesel introduced in the previous section, it can be seen how the cost of electricity is 67% lower than the one of diesel on a per-km-basis. It has to be reminded that the price of electricity considered is dependent on two very important variables: the overnight price discount, which is not the same in every country, introducing a high degree of variability on a national level and the average electricity price of the EU28 area. This latter value is dependent on the energy mix, that is the resources used to produce such electricity, which vary a lot from country to country. For example, France has a very low price of electricity, thanks to the presence of nuclear plants, while islands such as Malta have a price that is 2-3 times higher due to the lower accessibility to energy resources and the dependence on the importation from other countries. On the other side, the cost of electricity may change in the years to come, increasing or decreasing, depending on the investments of each country in renewable energies. As a matter of fact, the more countries invest in renewables, and in storage technologies to be able to keep the energy produced during lower demand times (such as late morning or early afternoon), the more they will be able to cover the upfront capital costs and shorten the break-even point. Furthermore, technology advancements such as nuclear fusion may be able to provide a clean and safe energy resource, potentially infinite and "free", as is the case of the research deuterium-tritium plants which claim to be able to produce, during the reaction, the resource necessary for its maintenance. This argument shows how the outcome of this paper has to be considered as an upper level analysis of the market and shouldn't be taken into account for comparisons on a national/regional scale.

Moving forward with the analysis, the next costs to be considered are those related with the maintenance of the vehicle. This factor is another very important component, together with fuel costs, of the operational costs of a commercial vehicles fleet. It is a group of costs, including the annual cost of acquiring and repairing tyres, maintenance, both preventive and according to the manufacturer indications, and the annual cost of breakdowns. The last two parameters include the workforce, spare parts and oil (for ICE vehicles). Being such a wide group of costs, it heavily contributes on the calculation of the TCO. Due to the very low adoption of electric LCV, data on the actual costs of maintenance for this category is not yet available. On the other side, researches and publications base their calculation on reduction factors related to the costs of conventional ICE commercial vehicles. For such reason, the starting point will be calculating the current costs that logistic services providers incur in when managing the operations of their fleet. The research of Earl et al. (2018), which is based on the impact assessment of the European Commission, considers maintenance and repair costs as being equal to 12.500 € per year. This value is calculated for heavy-duty long-haul trucks, which on average travel much longer distances and carry heavier weights, which have a great impact on the wear and tear of the moving components of the vehicle, such as suspensions, breaks, transmission and many others. As a consequence, this value is expected to be much smaller for LCVs and can be derived from the analysis of Advance Fleet Management Consulting, a Spanish small enterprise which relies on the deep knowledge of its founder José Miguel Fernández Gómez. After studying in the best engineering universities in Europe (Politécnica de Madrid and KTH Stockholm), he worked in logistics companies and as a research fellow for INSEAD, and then decided to fund the aforementioned company to share his knowledge with others. His report of 2017 identified that, for a vehicle traveling 75,000 km per year, considering 225 working days per year, the average vehicle costs for maintenance account to 7,850 € per year. The travel conditions considered are typical of a regional or national operating MDV, while for an LCV (even though we consider vehicles up to 7.5 tons) the average annual mileage is expected to be smaller. We will assume that on average an urban logistics LCV, including sporadic extra-urban activities, will travel 70 km per day, for 300 days a year, much more frequent than the aforementioned base case, limiting stops to maintenance and public holidays. Assuming also that the cost indicated above can be considered directly proportional to the km travelled per year, a value of 2,200 € per year.

The calculation of the corresponding maintenance costs for electric LCVs follows the paper of Earl et al. (2018), which estimates half of the costs of a conventional ICE commercial vehicle. This strong assumption is justified by evidences gathered from lease companies by Stewart and Dodson (2016) for ULEVs, particularly battery electric cars. The latter have fewer wearing parts, which are all the moving parts of a vehicle subject to friction and aging, they do not require regular oil changes and have reduced brake wear due to regenerative braking. Furthermore, this advantage increases with time, when older diesel vehicles experience higher costs for component failures such as fuel injectors, turbochargers (Stewart & Dodson, 2016). As a result of these reasons, and the simpler drivetrain in general of electric vehicles, which reduces the overall number of parts that could require maintenance, the maintenance costs considered for the electric LCV will be equal to 1,100 € per year.

The last component that should be taken into account for the calculation and comparison of the operating costs is the group of costs related with the taxes and incentives. Tax reductions and exemptions, in addition to government incentives are key for the mainstream adoption of electric vehicles, as mentioned before. Their importance in the passenger cars market has been proven by recent exponential increase in sales and the shift of many manufacturers to product mix including many electric or hybrid vehicles. The effect of such measures, together with all the advantages that the adoption of EV brings, described in previous paragraphs, shows promising trends of cost competitiveness compared to ICE cars. As shown in exhibit 14, the research of Slowik & Lutsey (2016) highlighted how, the consecutive phase-in and phase-out of different incentives' schemes would achieve the cost parity of 100-mile (160 km) electric range cars around the 2020–2021 time frame. As can be seen from the top part of the graph, incentives can gradually be reduced as market grows, while complementary policies and performance standards have to be maintained and strengthened as to address charging infrastructure and consumer awareness barriers and to sustain market growth of the new technologies. Concerning all the incentives and tax reductions that directly affect the TCO of a commercial vehicle, four main categories can be identified:

- Registration tax is a one-off payment for registration with a government authority when purchasing a new vehicle. In 2014, 20 out of 28 European countries had implemented a vehicle registration tax (Yan, 2018) and, in most of them, BEVs are exempted regardless of car or van model (in Norway they are even exempted from VAT, which is always the case for commercial vehicles). Once more, the most advanced regulation system has been enacted by Norway, with a continuous CO_2-based registration tax structure, which means that each g/km of CO_2 intensity is charged, differently from other countries where charges are dependent on ranges of CO_2 emissions.
- Annual circulation tax is a yearly payment for using a vehicle on the road. This tax is applied in the vast majority of EU countries as well, in particular 21 of 28 implemented it before 2014 (Yan, 2018). Differently from the previous case, only in some countries BEVs are exempted from the annual circulation taxes, such as Germany, while in Ireland for example ZEVs are charged a reduced fee.
- Congestion charges, which are applied every time that a vehicle needs to enter the urban or central area. From the database provided by the CLARS (Charging, Low Emission Zones, other Access Regulation Schemes), the map in exhibit 15 is drawn. It can be seen how only a minority of cities apply tolls for entering and circulating in central urban areas. As a matter of fact, the only country where this policy is applied massively is Norway, where 8 cities in

total, including Oslo[10], apply a congestion charge, which is proportional to the emission's class of the vehicle itself. Using as a reference the city of Oslo, euro6 and hybrid commercial vehicles, which are the most advanced technology at the moment, pay on average a daily toll of 12-16 € depending on whether they enter the city in the rush hour or not, while BEVs are exempted from it. The second most stringent congestion charging scheme is the one applied in the city of London, where the access toll charge corresponds to 13 € per day, and fines for non-compliance that can reach 200 £. London is one of three cities in the UK that adopted such policies, together with Liverpool and Edinburgh. Last but not least, the city of Milan, in Italy, has been one of the firsts to introduce congestion charges, in particular applied to the historical city centre, known as zone C. In this case, commercial vehicles are subject to a reduced fee of 3 € per access. All the other cities, that are somehow marked in the map in exhibit 15, either block certain vehicles from entering the city centre or they prevent the access in certain hours of the day. Still, this additional cost will be considered for ICE vehicles as to allow this research to be up to date also for the following years when congestion charges are expected to be adopted by a larger base of municipalities.

- Subsidies are applied directly on the final price of the vehicle to the customer. A particular version of subsidies, called "feebate" or "bonus-malus", has been gaining success in Europe in recent years. This particular solution combines a subsidy for low-emission vehicles and an additional charge for high-emitting ones. From the database of the European Automobile Manufacturers Association it can be seen how Italy and France already adopted it, with bonuses that can reach 6,000 € and maluses of up to 2,500 €. Other countries, that are expected to adopt this solution in the years to come, still rely on conventional incentives, up to 4,000 € in Germany, 5,000 € in Ireland, 6,000-8,000 € in Spain depending on the weight, 20% of the vehicle price in the UK, with a maximum incentive of 9,075 €.

Although such incentives can be seen as a very expensive way for governments to promote the adoption of electric vehicles, the research of Slowik and Lutsey (2016) demonstrated how, in the US case, the net present value of subsidies and incentives becomes positive within 5 years of implementation of such schemes, as can be seen from figure 20. In the scenario considered in the aforementioned paper, 5 million EV sales are expected in 2030, which is much lower than what expected form other papers in the field. For such reason, it can be said that the NPV will become positive much earlier and the cumulative benefits of the incentives will far

[10] In addition to Bergen, Haugesund, Kristiansand, Namsos, Stavanger, Tonsberg, Trondheim

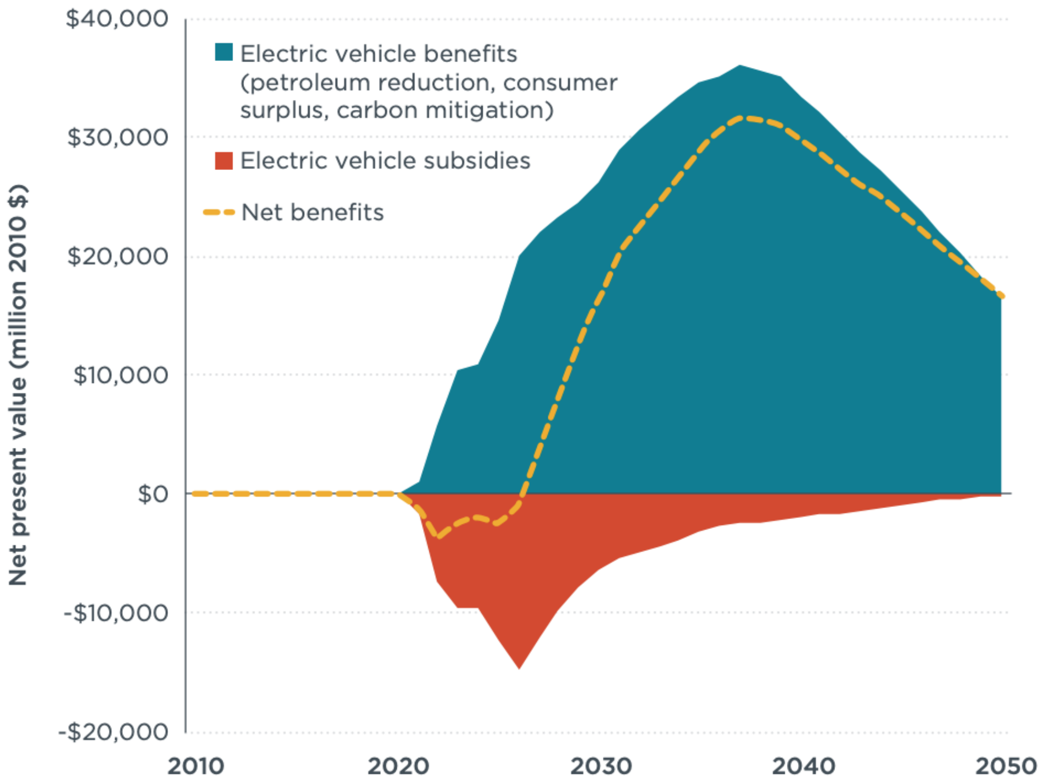


Fig. 20 Estimated NPV of costs and benefits of incentivising EV adoption in the US (source: Slowik & Lutsey, 2016)

outweigh the costs (in the figure benefits are 6 times bigger than costs). This should be an incentive for other countries to follow the example of Norway, where, thanks to the subsidies and tax reductions, the TCO of an e-LCV is already lower than that for a diesel vehicle (Mehta et al., 2019).

Finally, the last cost component to be considered is the installation cost of the charging stations. This cost is charged to the final customer, hence the delivery services provider, since the case of overnight charging inside the warehouse is considered. When converting the vehicle's fleet from ICE vehicles to BEVs, the company must take into account the need of installing one charging station per vehicle. Using the available data on the internet and double checking the different sources, an average value of 5,000-6,000 € is normally charged, including both the hardware and the installation costs. These stations are more expensive than conventional home ones due to the necessity of additional components and software to manage the high demand of electricity derived from the high number of vehicles charging at the same time. In this case a normal 230V station is considered, since it should be able to charge the battery in max. 8 hours. Otherwise, fast DC stations could cost up to 50,000 € and there would be a risk of shorter lifetime of the battery as introduced in the previous chapter.

Gathering the available data from commercial vehicles manufacturers, the price for an MDV, in the range of 4.5-5 tons GVW, spans between 30,000 € and 50,000 €, depending on the dressing (closed van or "trailer") and the equipment chosen. Considering the different configurations and the scope of this analysis, the average vehicle chosen for the comparison of the TCO has a GVW of 5 tons (mean value of the 3.5-7.5 range) and is priced at 35,000 €. To this, it must be added the registration tax, which is paid only by ICE vehicles, which is in the order of 3,000 €, considering an average of the different EU tax schemes, which tax different vehicles according to their CO_2 emissions class (or precise value in g/km, as it is the case of Norway) and GVW. This value has to be compared with the average price of the electric commercial vehicle used as sample of this dissertation. The selling price of it can be calculated knowing the cost of the battery and drivetrain, respectively using the value in €/kWh and €/kW determined before, and their incidence on the final price, which is in the range 42-70%, as can be derived from figure 17. In order to calculate these costs, the sample vehicle must be dimensioned in terms of output power and range needed. Using the data available from exhibit 10 on the existing electric LCVs and MDVs, restricting the GVW to the range 3.5-7.5 tons, the following table was built, obtaining the sample average vehicle shown in the last row:

Manufacturer	Range	Power (kW)	Battery (kWh)	GVW
BYD	250	150	145	7.3
Daimler	100	185	70	7.5
Daimler	100	110	48.5	6
EFA-s	100	91	61	7.5
EMOSS	160	120	62	7.5
EVI	145	200	99	7.3
Iveco	110	80	63.6	5
Motiv Power	130	150	106	6.6
ORTEN	100	90	72.5	7.5
Smith	120	90	40	4
Smith	65	120	40	6.4
US hybrid	120	120	36	4.5
Average	**125**	**125,5**	**73,22**	**5**

Table 1 Commercially available electric MDVs (data from Moultak et al., 2017)

The GVW is 5 tons, which is exactly the mean value of the considered range, which justifies choosing this average vehicle as the sample for the comparison. In addition, the range obtained, 125 km, is exactly the expected value, since it would allow to perform daily activities (expected to be in the range of 60-75 km), without draining the battery, while guaranteeing additional range in case needed. As a consequence, this value would allow the adoption of an electric fleet without sacrifices for the logistics services provider. Using the following formula, the battery cost is calculated:

$$Battery\ cost = \frac{Battery\ capacity * unitary\ kWh\ cost}{Usable\ energy\ capacity}$$

Obtaining a value of 13,525 € considering the previously mentioned unitary cost of 157 €/kWh and a usable capacity of 85%. The division by the usable capacity is done since it is expected that the battery size shown is the actual usable capacity, while the installed one is bigger in light of the phenomena introduced in the beginning of the current chapter. In addition to this, the drivetrain cost is computed using the unitary cost of 22,9 €/kW and the fixed cost of 700€, obtaining a value of 3,574 €. Summing up the two values, and considering the worst final price incidence of 43%, the price obtained for this vehicle is 39,765 €, which is below the price expected from the average of commercially available vans and trucks. The most similar vehicle currently in production is the Iveco Daily 5t electric, which is priced at 95,000 €. This vehicle has a 250 km range, meaning that, if the price difference is attributable only to the battery size, considering a price incidence of this component equal to 35%, a reduction of 16,625 € could be obtained for a battery half the size of the aforementioned. On the other side, the reduction of the battery price is expected to reduce also its incidence on the final price of the vehicle (the considered structure is already 2 years old), which means that the final price of 39,765 € calculated before would be much higher. In addition to this, the average unitary cost of the battery is higher than the 157 €/kWh considered, since the researches used as a reference consider also batteries at a research stage and high volume producers such as Tesla and LG-Chem, whose clients are, currently, only passenger car manufacturers. In the following conclusion, a much more realistic value will be considered, given the fact that the available data gives a too optimistic scenario as shown by the calculation performed. A value of 180 €/kWh will be considered for the unitary battery cost, corresponding to the upper bound of the reference research of Fries et al. (2017), and a price incidence of the battery-drivetrain module of 35%, which leads to a final vehicle price of 54,500 €.

Taking into account the two aforementioned vehicle's prices, a simplified analysis of the future cashflows is performed for the two different technologies. Before describing the results of such computation, the "boundary conditions" must be introduced, since some factors are calculated based on such assumptions. First of all, the annual mileage, which is used to calculate both the fuel costs (knowing the lt/km consumption) and the congestion charges, is calculated considering an average daily activity of 70 km and 300 working days per year, obtaining a value of 21,000 km per year. For the calculation of the urban charges, an 80% share of urban activity is considered, since, as said before, extra-urban trips will be limited to occasional deliveries, and 10 € per access are applied, considering that, for the purpose of this toll, business companies will not be receiving any discount (as it happens for other taxes). An additional annual charge is the one deriving from the circulation tax, which is assumed to be 300 €, as the average of circulation charges applied in different European countries. Last but not least, an average subsidy of 6,000 € is applied to the initial cost for the electric vehicle, although it will not be granted by governments in the future when the reduced cost of batteries will guarantee a cost parity without the need of any incentive. It has to be remembered that this is a simplified model, since it does not take into account insurance costs, spare parts replacement (for this reason the 5 years' timeframe was chosen) and additional costs that the logistics services provider may incur.

As a result of these considerations, table 2 and 3 are built, using as discount rate for the future cash-flows the current average EU inflation rate, equal to 1.6%. It can be seen how, in the 3rd year, the TCO of the electric vehicle is already lower than the one of the ICE vehicle, thanks to

ICE Vehicle	**0**	**1**	**2**	**3**	**4**	**5**
Initial cost	35.000,00	-	-	-	-	-
Charging stations	-	-	-	-	-	-
Registration tax	3.000,00	-	-	-	-	-
Subsidy	-	-	-	-	-	-
Maintenance	-	2.200,00	2.200,00	2.200,00	2.200,00	2.200,00
Circulation tax	-	300,00	300,00	300,00	300,00	300,00
Congestion charges	-	2.400,00	2.400,00	2.400,00	2.400,00	2.400,00
Fuel cost	-	2.031,60	2.031,60	2.031,60	2.031,60	2.031,60
Total	38.000,00	6.931,60	6.931,60	6.931,60	6.931,60	6.931,60
Discounted	38.000,00	7,042.51	7,155.19	7,269.67	7,385.99	7,504.16
TCO	**38.000,00**	**45,042.51**	**52,197.70**	**59,467.37**	**66,853.36**	**74,357.52**

Table 2 Future cash-flows in € (simplified model) for the 5 years' timeframe for an ICE 5 tons van

much lower operational costs of the BEV van.

BEV	0	1	2	3	4	5
Initial cost	54.500,00	-	-	-	-	-
Charging stations	5.000,00	-	-	-	-	-
Registration tax	-	-	-	-	-	-
Subsidy	- 6.000,00	-	-	-	-	-
Maintenance	-	1.100,00	1.100,00	1.100,00	1.100,00	1.100,00
Circulation tax	-	-	-	-	-	-
Congestion charges	-	-	-	-	-	-
Electricity cost	-	664,44	664,44	664,44	664,44	664,44
Total	53.500,00	1.764,44	1.764,44	1.764,44	1.764,44	1.764,44
Discounted	53.500,00	1,792.67	1,821.35	1,850.50	1,880.10	1,910.19
TCO	**53.500,00**	**55,292.67**	**57,114.02**	**58,964.52**	**60,844.62**	**62,754.81**

Table 3 Future cash-flows in €(simplified model) for the 5 years' timeframe for a 5 tons commercial BEV

It has to be remembered that the vehicle considered has a range of 125 km, which justifies the lower upfront capital cost of the vehicle. In case we were to perform the comparison with the Iveco Daily 5t electric, the much higher price of the vehicle would be offset in a much longer time, although the longer range would reduce even more the fuel costs and consequently limiting the PBT.

Additionally, 3 parameters would have to be considered if performing a sensitivity analysis of this simplified case:

- Congestion charges were applied even though just a few cities already implement them. In case this toll is removed from the model, the PBT shifts to the 5th year and the operational costs reduction is limited to the fuel costs and circulation tax.
- Subsidies still play an important role in the TCO cost-parity, since they are able to offset the investment in the charging stations and part of the additional cost deriving from the batteries. In some countries, this incentive is not provided and, in general, subsidies are expected to gradually phase-out as electric vehicles become mainstream, since they represent a considerable cost for governments and municipalities.

- As can be derived from the trends in figure 18, the average cost of battery packs is expected to decrease by 7% per year according to Lutsey & Nicholas (2019). This means that, in fact, subsidies will not be necessary anymore and the widespread adoption of electric vehicles will be spurred by sanctions and additional taxes charged on conventional ICE vehicles.

To conclude, the result obtained represents only one application for which, in case all the assumptions are coherent with real case scenarios, the cost parity is already possible for commercial BEVs, and shouldn't be generalized. In fact, other papers highlight how the cost parity is still to be achieved, although this could require just a few years. An interesting paper that could be used as a benchmark is the research of Heid et al. (2017), for the McKinsey centre for future mobility, in which 27 commercial vehicles' segments where analysed in different regions. The first very interesting result of this paper is the review of the TCO parity timing for the different vehicle segments and regions of the world, as shown in exhibit 16. As can be seen, both electric LCV and MDV applications are expected to break-even before 2021 in Europe, which may explain why, for the scenario considered in this paper, cost parity seems to be already a reality. On the other side, they also identified a niche application which was claimed to be cost-effective already in 2017, the so-called "regional light-duty truck hub-and-spoke delivery" (Heid et al., 2017). This particular case refers to the regional grocery delivery for shops and restaurants and is described in detail in exhibit 17. In this particular situation, the van could charge its batteries while delivering goods at the restaurant or shop, during loading and unloading times, allowing the installation of smaller batteries, and consequently reducing the upfront capital cost incurred.

6 IDENTIFICATION OF COMMERCIAL BEVS OPERATIONAL LIMITS

6.1 External factors impacting EV performance

The total cost of ownership parity is a necessary condition for the adoption of such technology, although it is not a sufficient one. Battery electric vehicle have very limited optimal working points, due to the impact of external factors on the discharge of the batteries and the efficiency of the electric motors. As highlighted by Tesla on the FAQs page of their website, there are a series of conditions and behaviours that may impact the range of the vehicle:

- High driving speeds
- High cabin air conditioning or heating usage
- Low ambient temperatures
- Inclement weather such as rain, snow and headwinds
- Stop-and-go driving
- Short trips
- Uphill travel

Some of them are behavioural conditions, meaning that they depend on the specific driving style of the driver, such as high driving speeds, short trips and stop-and-go driving. In particular, the last two are the consequence of frequent changes of speed, which are typical of urban trips in bad traffic conditions. The lower fuel efficiency that derives from these factors affects both BEVs and ICEs, in similar measures. On the other side, high driving speeds are the consequence of longer trips on highways, where a minimum speed must be maintained. This factor, together with uphill travel, are dependent on the specific route. Because of this, it will be seen later that the simulation tool used requires as input both speed and slope profiles (these are almost able to fully characterize the vehicle consumption). Lastly, the third group of parameters is related to atmospheric conditions, in particular temperature, which can have two effects on the vehicle range: low and high temperature can reduce the battery capacity and/or life, and can also force the driver to turn on A/C. Before getting into the details of the effect of temperature on the battery, A/C can have a strong impact the performance of the car, by consuming a lot of energy in case of extreme temperatures, particularly for cold weather. When the temperature gets very low, many degrees below zero, the battery performance drops (as will be seen later), and the need of heat inside the vehicle can double the range reduction up to more than 40%[11]. For such reasons, companies such as Bosch have developed thermal systems that rely on the heat pump technology to recover the weather losses. Such components are designed to transfer thermal energy out of the cabin during hot weather (functioning as an air-conditioning compressor), and to bring thermal energy from power components or outside into the cabin in cold weather. As claimed by Bosch, this device is able to recover up to 20% of the cold-weather energy loss, and it's already commercially available on BMW, VW, Audi, Jaguar, Nissan and Kia cars.

The effect of temperature needs to be treated separately because of its complexity and the potential effect it can have on the battery. As emerge from the research of Ma et al. (2018), the acceptable operating temperature of Lithium-Ion Batteries (LIBs) is between 20 °C and 60 °C, while the optimal temperature range is 15 °C – 35 °C. For temperature which are above or below these values, the battery will degrade fast, losing its capacity or increasing the risk of facing safety problems. In general, although most effects of temperature cause the change of electro-chemical reaction rate in batteries, following the Arrhenius law, impacts from temperature can be divided into two categories

- Low temperature effects: these impacts are mostly caused by the environment's temperature. It was found by Ma et al. (2018) that the State-Of-Charge (SoC) of the battery decreases by ~23% when the operating temperature decreased from 25 °C to −15 °C. The first reason is found in the effect of low temperatures on the property of electrolyte. With the decrease of temperature, the viscosity of the electrolyte will increase, which will reduce the ionic conductivity, hence the speed at which Lithium ions can travel from the anode to the cathode. A second effect of low temperatures is

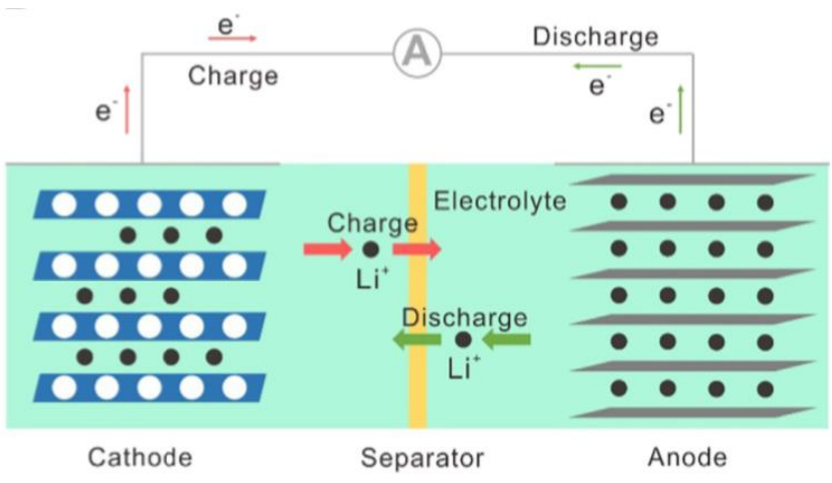


Fig. 21 Schematic of the operating mechanism of LIBs (source: Ma et al., 2018)

11 https://www.greencarreports.com/news/1124387_can-heat-pumps-solve-cold-weather-range-loss-for-evs

the increase of charge-transfer resistance that contributes to the performance degradation in LIBs. Charging a battery at low temperatures is thus more difficult than discharging it because of the different charging resistance of the two cycles. Lastly, low temperatures can trigger the polarization of anodes, the so-called lithium plating, which can slow down even more the charging process.

- High temperature effects, which are mostly attributable to the high internal temperature of LIBs during operation rather than the environmental temperature. The first thing to be considered is the heat generation, associated with charge transfer and chemical reactions during charging and discharging. As can be seen in exhibit 18, there are many processes that can generate internal heat, both through reversible and irreversible processes. A second effect, which instead is caused by external high temperatures, is called aging, which is responsible for both a reduction in the performance of the battery and a reduction of its lifetime. Increasing the operating temperature of LIBs above the optimal scope will accelerate the aging process and lead to the degradation of LIBs. The third and last process that can be triggered because of high temperatures is the thermal runaway. This is can be caused by defective manufacturing or improper handling, resulting in exothermic reactions in the operating batteries when the battery is exposed to high temperatures. Being exothermic reactions, a chain effect is triggered and when the heat endurance of the battery is finally exceeded, fire and exploration may occur. There have been cases in the electronics industry, such as Apple and Lenovo computers or Samsung smartphones being retired from the market due to small explosions of the LIB. This may also be the reason of recent Tesla model S and X spontaneously catching fire in the United States.

While most of the effects can be controlled via appropriate internal temperature measuring systems, the performance of the EV will still be affected by extreme external temperatures. Countries like Norway and The Netherlands, between the most advanced countries in terms of EV sales, proved that this issue is not seen as a strong limiting factor by private customers. On the other side, commercial EVs can be impacted in a much stronger way by it, since daily operations can be limited in countries where extremely low or high temperatures are reached.

In order to perform the economic analysis in the previous chapter, a simplified model was built, by fixing many of the parameters discussed above. The temperature was completely excluded from the analysis, although a reduced range (due to extreme temperatures) of the battery would imply more frequent charges. This eventually leads to higher electricity cost per year for the end-customer and consequently increases the pay-back time of the vehicle. Then the average vehicle consumption was fixed, so that, by multiplying it times an assumed annual mileage, the annual fuel costs would be obtained. As it was previously highlighted, many factors can contribute to variations in the engine and electric motor efficiency, leading to a relatively high volatility of the vehicle consumption. For example, high speed trips will result in EVs consuming much more than conventional ICE vans, while uphill routes can be a tougher burden for combustion engines. This is much influenced by the last parameter that was fixed, which is the mix of urban and extra-urban trips in the annual mileage. A share of 80% urban was chosen to reflect the scope of the analysis, being it urban logistics and delivery vehicles. These usually start the day in a central warehouse, located few kilometres outside of the urban area with easily accessible from the highway. The daily route is then characterized by a large majority of urban destinations, separated by short distances and relatively flat roads. This is the ideal scenario for

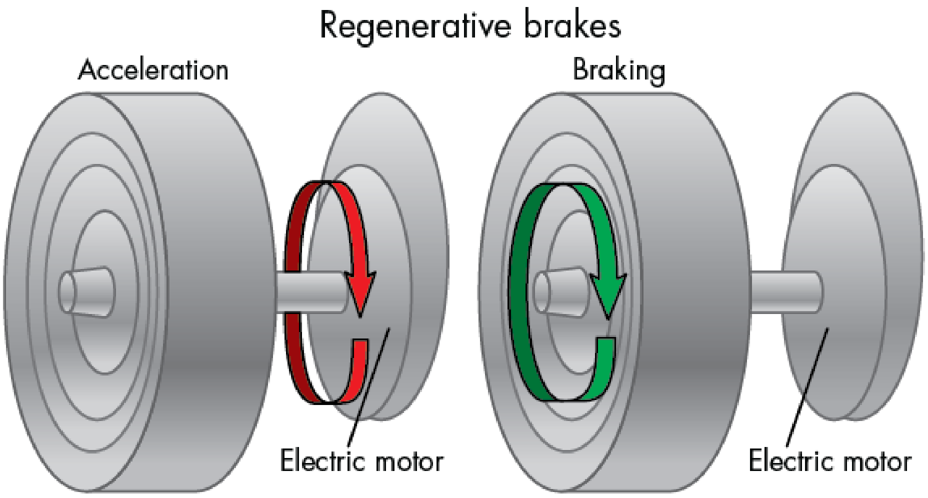


Fig. 22 Regenerative brakes scheme (available at: https://auto.howstuffworks.com)

EVs, since the route itself is not so energy demanding for the electric motor, and the short trips allow to regenerate a lot of breaking energy. Regenerative breaking allows electric and hybrid vehicles to recover part of the energy that would be lost during the breaking phase, by reverting the rotation of the electric motor axis and transforming into a dynamo. The energy generated is then stored in the battery of the vehicle. This technology was first developed for the racing industry and tested in Formula 1 and endurance races since 2007-2008. Toyota became famous with the self-charging hybrid, allowing its vehicles to travel on average 50% electric in urban areas. The fuel savings deriving from this technology explain why hybrid vehicles reached such high penetrations in the European market. They also partially justify the TCO cost parity achieved by LCVs in the previous chapter.

That being said, it is expected that a change of the scope would necessarily mean a different behaviour of the electric motor and the battery. In that case, the driving pattern would be different, as well as the average slope of the road and the mix of urban vs. extra-urban, compared to the scenario used for the economic analysis. For such reason, this chapter is meant at identifying potential extreme situations in which electric LCVs are still not a viable solution, due to business constraints. There are situations in which the route is too demanding for the electric engine and the battery, or it is not possible to charge on-the-go. The case presented in the research of Heid et al. (2017), of regional hub-and-spoke distribution, represented an ideal conditional for EVs outside of typical urban applications. In that case, the possibility of charging the van during the loading and unloading periods allows not only to reduce the TCO, thanks to a smaller battery, but also to easily carry on routes of up to 200 km. That example represented a different scope, more demanding than the typical urban logistics scenario, still viable from both economic and business perspective. By removing one or more of the assumptions that allow the Heid et al. (2017) case to reach cost parity and be operationally possible, the analysis that will follow will determine whether there are more extreme situations in which commercial BEVs are still a realistic solution. Leaving aside the TCO, the analysis conducted in the next section is aimed at understanding whether electric LCVs are still able to complete daily tasks even when it is not possible to charge on-the-go, nor return to the hub more than once a day. Starting from the data gathered on a diesel van, a simulation tool will be used to derive the corresponding data of an electric vehicle with the same GVW. The consumption and other parameters will be compared to identify whether the limit condition is reached.

6.2 Electric vehicle limit mission profile definition

The most challenging scenario for battery electric vehicles, compared to conventional combustion engines, can be defined by changing one of the parameters described in the chapter's introduction: the mix of urban and extra-urban trips. In Italy, in particular for the central and southern regions, a higher % of extra-urban journeys means more frequent changes of slope (due to the hilly landscape), poorer road conditions and intense traffic, especially when close to big metropolitan areas. When added to higher speeds maintained for longer periods of time, it can lead to higher consumption levels compared to ICE vehicles. This effect is even more evident for LCVs, for which the increased load amplifies the inefficiencies of the battery and the engines.

To perform the data collection, one of the leading Italian companies in the field of IoT solutions for the localization and management of moving vehicles, people and goods was selected as partner for the research. Born in 1996, and thanks to big investments in R&D, WAY s.r.l (Where Are You) is now able to offer a wide range of services and products for companies, from GPS & monitoring devices, smartphone apps for fleet management and up to software platforms to control maintenance drones. Through one of such devices, WAY recorded the data of the daily operations of a 3.5 tons Iveco Daily traveling for 152.7 km in the region in the north of Rome. This vehicle is owned by a company that works in the:

- Design, construction and maintenance of copper communication networks
- Design, construction and maintenance of new generation communication networks
- Installation and test of mobile radio systems

The vehicles allocated to such activities normally leave the central hub, located next to the natural reserve of Nazzano (Lazio, Italy), or the house of the employee, to perform installation and maintenance services to the network of fixed and radio mobile devices within a certain range and then come back at the end of the day. In this case, the daily route is not fixed, and will depend on the specific tasks to which the operator is assigned on that specific date. Contrarily to regional hub-and-spoke distribution, or urban delivery and logistic services, in this case it is not possible for BEVs to rely on public charging and/or destination charging (e.g. warehouses), since the locations to be visit vary on a daily basis and depend on specific contracts with the clients. The investment to build an appropriate grid of charging stations to secure daily operations would require a significant investment and the TCO would be achieved only if the fleet size is scaled up to dozens of vehicles. This profile mission represents a very challenging scenario for BEVs and the ideal opportunity to try and identify the current limits of this technology. It might be that the simulation results go against such assumption and that even for this challenging mission profile commercial BEVs are still viable from a technical perspective. Nonetheless, when performing a sensitivity analysis, it is possible that the SoC (State-Of-Charge) of the vehicle during the day cannot cover for consumption fluctuations derived from higher road traffic, farther unexpected destinations or worse road surface conditions (higher tear and lower engine efficiency). In all such cases, the need of charging stations in strategic locations would show up again and a new economic analysis to understand whether the cost parity can be achieved during the life of the vehicle.

6.3 Diesel LCV preliminary data analysis

The preliminary analysis will be conducted taking into consideration all the parameters that, as highlighted in the introduction of the chapter, can influence the performance of a BEV. Lastly, before analysing the results of the simulation, the consumption of the Iveco daily diesel will be analysed to try and predict the expected behaviour of the corresponding Iveco Daily electric. It has to be pointed out that, due to the nature of the mission profile, the GVW of the vehicle does not play an important role. Since the scope of the daily operations may vary on a daily basis, it can be that most of the time the vehicle travels half empty, carrying enough equipment and load to only perform normal maintenance services. Furthermore, to measure the exact load with the same frequency of the other parameters, a particular device should be installed, which is also available only for some vehicles. Nonetheless, since the Iveco Daily electric is analysed using the results of a software simulation, it was possible to consider also the effect of the load during the same trip. In that case, as it will be shown later, a linear reducing trend was assumed, as if the vehicle was loaded in the morning with all the devices to be installed during the day and that these are installed progressively at each stop of the van (in a similar way to a delivery van). For this reason, the BEV simulation represents the worst-case scenario and in case it is still a viable solution from a business perspective, is should be able to face even the most challenging daily tasks.

The impacting variables can be divided in external factor, namely the weather, the road conditions and the traffic, and internal factors, meaning all those related to the route and the driving pattern. The first factors to be considered will be the internal ones, since are the most impactful on the vehicle performance and closely related to the business operations. These are all data that were retrieved directly from the measuring onboard system, or that could be derived from such data using simple formulas and assumptions. Due to a lack of detail in the 1st measurement, a second test vehicle was requested to WAY, as to ensure that the data were reliable enough to make considerations and to derive indirectly key parameters such as the slope profile and the vehicle consumption. Nonetheless, real data always need to be appropriately filtered before analysis, which is why, even after the second measurement, part of the data had to be neglected because double, missing values, incongruent numbers and other reasons. Even though it involved only a small percentage of the total amount of collected data, it explains why the slope and speed profiles, and also the detected coordinates, are not perfectly aligned. The second and final recording was performed on the 30th of October 2019, during a total time of 12 hours and 52 minutes and with a time-step of 5 seconds, generating 4582 Excel lines of useful data.

The first variable measured by the on-board device is the position, derived from the longitudinal and latitudinal coordinates of the vehicle. By using a mapping software, fig. 23 is obtained, showing the trip that the vehicle performed on the 30th of October 2019 in the area northwest of Rome. By limiting the coordinates to the ones in which the vehicle stops, corresponding to the interventions that the operator needed to perform (excluding the very few in which the vehicle is waiting at a traffic signal), the map in Exhibit 19 is drawn. As it will become evident from the slope profile, this is a region full of hills, next to the Italian Appennino, representing a very challenging landscape for every kind of vehicle. Even though the trip start at 6.30 in the morning and the vehicle comes back to the starting point only at 19.20, more than 70% of the measurements were done in the first 6 hours, until 12.20. Out of the 31 stops that are shown in

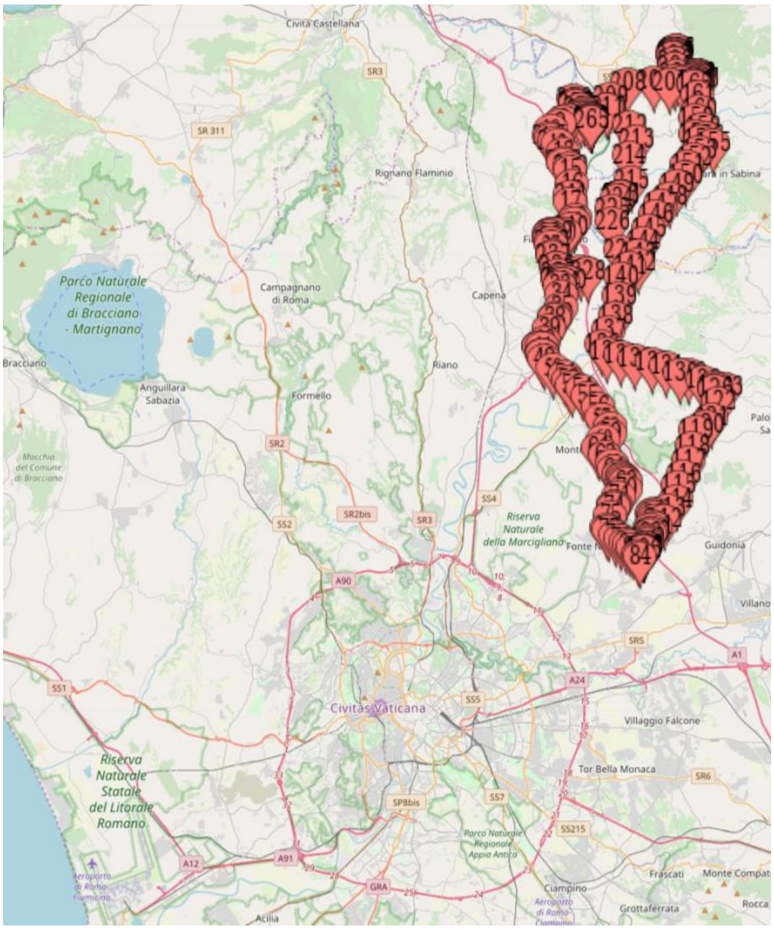


Fig. 23 Diesel vehicle 30/10/2019 trip (source: https://www.mapcustomizer.com)

Exhibit 19, 75% were collected in the same time frame, while the remaining ones correspond to the trip back to the central hub.

The second variable obtained is the speed, which is computed in time and can be used to estimate the activities performed by the operator. First of all, the resulting graph in fig. 24 clearly shows three macro-recordings:

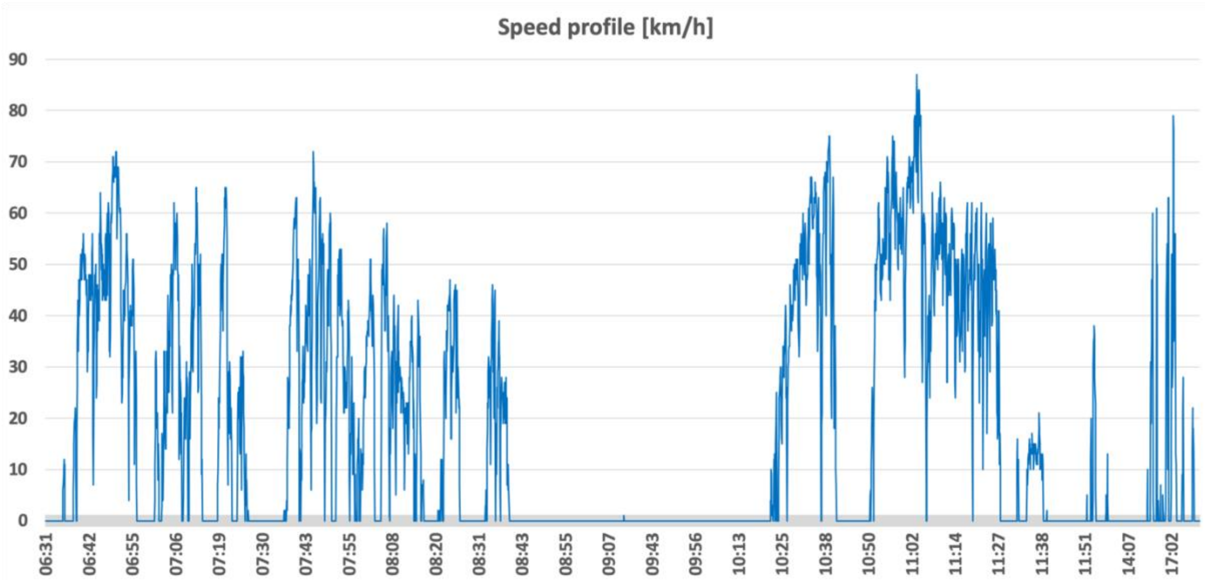


Fig. 24 Diesel vehicle speed profile

- The first one on the left, corresponding to the values collected from 6.31 until 8.40, which will be called "Path 1", characterised by continuous changes of speed and many stops. During the 2 hours and 10 minutes the average speed of the vehicle is 21.4 km/h and the velocity is below or equal to 60 km/h for more than 96% of the time. This trend may be explained by the data on the position of the vehicle, since around 8.39 the vehicle is stopping at the lowest point of the trip, marked as stop 13 in Exhibit 19. The trip taking up to this point is characterised by many small urban areas, in which the vehicle stops for 5 to 10 minutes breaks. In total, 5 of such breaks are recorded, the first one happening 25 minutes after start and then after 10, 40 and again 10 minutes respectively. This behaviour explains the continuous changes of speed and the abrupt accelerations experienced by the vehicle. As it will be seen later, this results in very high peaks of consumption. On the other side, it may be expected that during this phase the BEV simulation will show high energy recovery thanks to the regenerative braking system.
- The central portion of the graph, which goes from 8.40 until 10.22, is completely flat, meaning that the vehicle is parked (position 13 of Exhibit 19). For the purposes of the

simulation, these recordings are completely neglected, although they may be useful to describe the profile mission more in details. In fact, this long break can have two possible meanings considering the business of the company: a long and complex installation, or a troubleshooting/maintenance at a client's site. Furthermore, both situations can explain the series of stops that precede this event. On one side, in case of an installation, the stops may signify that the operator needed to gather the necessary components and equipment to perform the installations. On the other side, in case of troubleshooting, it could be that the final destination corresponds to the central unit of a network of radio/communication devices. Each stop corresponds to a specific check and that would explain why the duration is so short and regular. All these considerations given, and without any additional material, the second option seems to be the most reasonable one.

- The third and last portion of the graph, which will be referred to as "Path 2", correspond to the data gathered between 10.22 and 12.17. Even though at first notice Path 1 and 2 seems to be quite similar, both in terms of duration, number of recordings and trend, at a closer look it will be evident how different they are. First of all, in Path 2 the number of breaks reduces to 3, again of a duration of 5 to 10 minutes, but not uniformly distributed in time. Secondly, the speed of the vehicle is also very different, since in this case the vehicle is going much faster and reaching higher peak speeds (up to almost 90 km/h). On average, the vehicle is travelling at 29 km/h, and for more that 12% of the time the speed exceeds 60 km/h. This can be explained by the fact that on the trip back to the northern part of the region, there are just a few small cities in which the operator stops. For the rest of the time, the vehicle is probably travelling on highways, experiencing longer and lasting accelerations, resulting in a more defined speed trend (in between stops).

The remaining portion on the right of the graph, corresponds to the one after 12.17. In case of the speed profile, it is even more evident why the data collected in the afternoon (there is also a 40 minutes lunch break) should be neglected, since 91% of the recordings are done before 12.20.

The second important variable, which is the one remaining needed by Iveco's simulation tool, is the slope profile. In this case it cannot be derived directly from the recordings, since the only data of this kind available is the altitude, which is plotted in fig. 25. From this, the slope trend can be derived using both the altitude and the speed through the following formula:

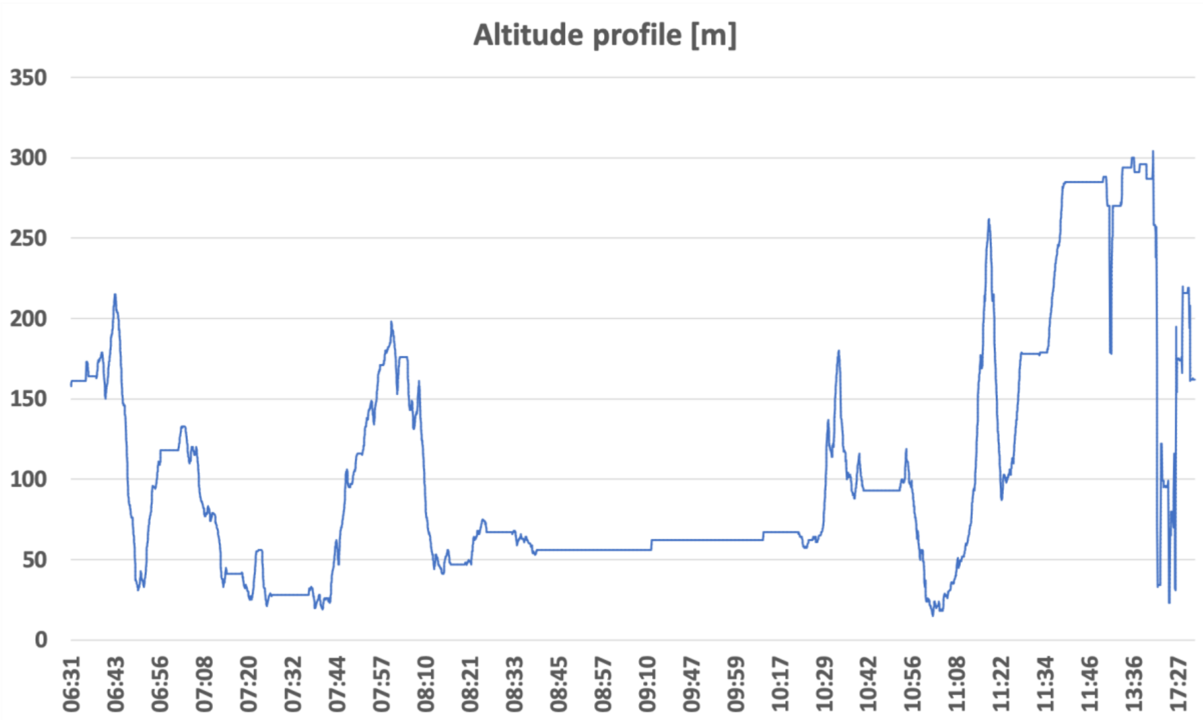


Fig. 25 Diesel vehicle altitude profile

$$slope_x\ [\%] = \frac{altitude_x - altitude_{x-1}}{speed_{x-1} * \Delta t} * 100$$

In the formula, Δt corresponds to the time step between two successive measurements, normally equal to 5 seconds. Even though this formula may be subject to high errors, due to the strong impact that both speed and time have at the denominator, it works very well for both Path 1 and 2. Furthermore, also in this case it is evident that the events after 12.20 play a neglectable role in the analysis, thanks to the filters applied. The resulting slope is reported in Exhibit 20, where all negative values correspond to downhill portions and vice versa for positive slopes. All values within the range ±10 % should correspond to urban areas, while all the uphill and downhill trips of extra-urban roads are defined by the peaks. This assumption could be wrong in case of very old villages (common in the centre of Italy, particularly Tuscany and Umbria), where steep stone roads are frequent in the ancient centre. Nonetheless, without additional information of the topography, and using the information available from satellite's pictures, the considered trip is restricted to the valley and hills around the Tevere river. In fact, it can be seen from the altitude trend in fig. 25 that, even though there are significant leaps, the average altitude is 104 metres. As in the speed profile, the graph can be split in the same three portions. For Path 1, there are frequent variations but of relatively small magnitude, reflecting the assumption of many consecutive urban areas. The flatter portions correspond to the same stops that were recorded in the speed profile. In Path 2, excluding the abrupt lower peak recorded around 12.00 (probably an error of the device), there are just a few very steep trends, even though the magnitude is much more significant than in Path 1. This is reflected by the slope profile in exhibit 19, where Path 1 is characterized by many peaks alternated by low slope portions, while Path 2 shows higher progressive slopes and a more defined (almost sinusoidal) trend.

By analysing the slope and speed profiles together, the root causes of the vehicle's consumptions can be derived. The diesel consumption is plotted in figures 26 and 27 and it is

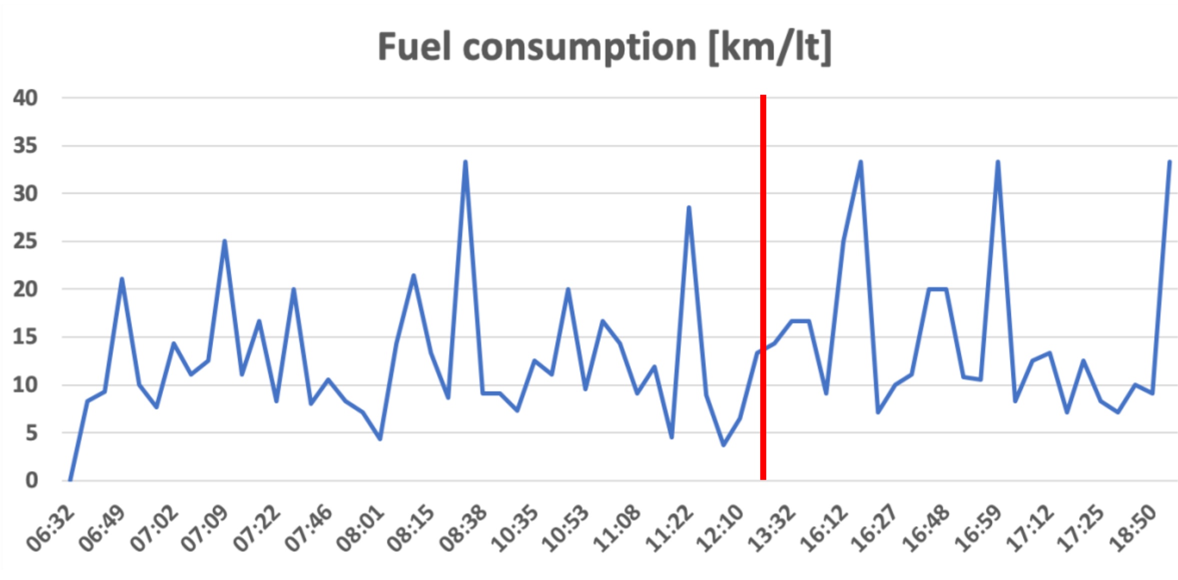


Fig. 26 Diesel consumption in km/lt

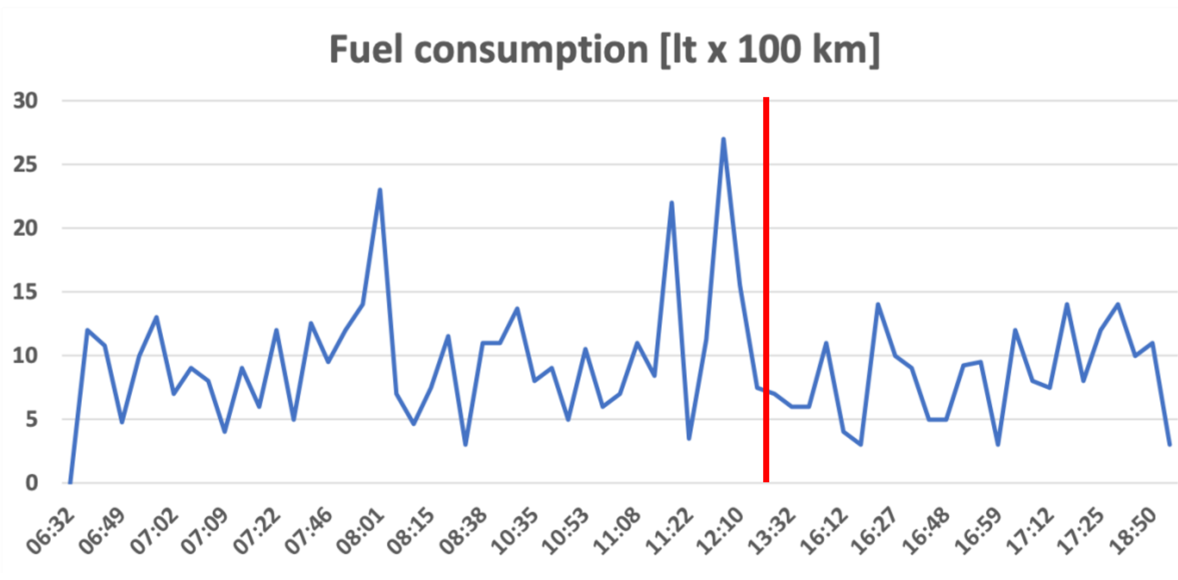


Fig. 27 Diesel consumption in lt/100km

derived from the data measured in the vehicle's tank. By measuring the total fuel used, and knowing the distance travelled by the vehicle calculated from the speed and the time-step, the fuel consumption is plotted according to the two most used units of measure (km/lt and lt/100km). The red line represents the last recording before 12.20. Even though in this case there is extensive data after this time "limit", the information coming from the speed and slope profiles is very scarce and does not allow to draw conclusions on the causes of such consumptions. For this reason, only the left portion of the graph will be analysed in detail. Starting form Path 1, the fuel consumption is perfectly in line with previous considerations, since the continuous changes of speed results in fluctuating consumption, even though the lower max. speed and the smoother altitude profile contribute in limiting the magnitude of the peaks. On the other side, Path 2 shows more evidently the combined impact of the speed variations and the altitude changes. In the first 45 minutes the consumption is marginally oscillating around 12 km/lt, which is the typical consumption of an LCV at moderate speeds in extra-urban cycles (keeping in mind that in this case the GVW has a minor effect). Thereafter, around 11.15, the vehicle crosses the region with very big altitude variations and the engine is also subject to intense and prolonged accelerations. This is possibly the cause of the two highest peaks in the central region, next to the red line.

Before drawing any conclusion on the expected BEV behaviour based on the trends here highlighted, the external factors must be introduced. Starting from the weather conditions, their effect can be neglected, since ideal conditions for the simulation were achieved on the 30th of October. As can be derived from many weather databases[12], the temperature during the day spanned from a minimum of 13 °C up to a maximum of 21 °C, perfectly falling within the optimal operating temperature range of BEVs. Furthermore, there was almost no wind and only one brief rain shower reported in the late afternoon, when, as highlighted before, the data gathered is much less valid than in the morning. Regarding the road conditions, it cannot be assessed without more detailed information on the specific trip (the frequency of data on the position does not allow detailed geolocation). In any case, this parameter should have a similar impact on both electric and combustion vehicle, meaning that in a comparative analysis it can be omitted. Lastly, the traffic conditions are also not impactful, since there are not periods of time in which the vehicle is frequently stopped or travelling at less than 20 km/h (the speed

[12] https://www.accuweather.com/en/it/rome/213490/october-weather/213490?year=2019; https://weather.com/it-IT/tempo/mensile/l/1d1a251383dc0d1bdbfb8efbc155374b376eff6f5232f36110b823e47362866e; https://www.worldweatheronline.com/rome-weather-history/lazio/it.aspx

profile of Path 1 is caused by the normal traffic conditions in urban areas, as explained before). Without additional information, it can be deducted that the fluctuations in the speed profile may be directly attributable to typical urban and extra-urban trips rather than intense traffic conditions.

The speed and fuel consumption profiles suggest that there may be some potential for the electric version of the Iveco Daily, since the numerous descending trends are imputable to breaks and downhill stretches, which could charge the electric battery via regenerative breaking. Furthermore, the recorded scenario does not represent per se a challenge for BEVs, since the diesel van was carrying a limited load. The following simulation, in which instead the GVW is assumed to play a bigger role (as for a logistics/delivery van), will help understand whether these expectations hold also in the worst-case scenario.

6.4 BEV simulation and behaviour comparison

In order to ensure consistency between the real data gathered for the Iveco Daily 3.5 tons diesel and the simulated BEV, the same OEM tool was used. The simulation software, which is based on Matlab and Simulink, receives in input the speed and slope profiles and generates a matrix of the following variables: battery rms (root mean square), voltage and SoC (State-Of-Charge), the electric motor speed and torque, and the vehicle reference speed, slope and travelled distance. For the scope of this simulation, the important parameters are those describing the battery behaviour. Before analysing the results of the simulation, it is important to list all the assumptions and considerations needed to launch the software:

- The simulation was performed for both 3.5 tons and 5 tons versions of the Iveco Daily electric. Even though only for the first version a direct comparison with the diesel van is possible, the 5 tons should represent the real challenging scenario for BEVs.
- The simulation was performed separately on Path 1 and 2 to avoid that neither the long break between 8.40 and 10.20, nor the inconsistent data gathered in the afternoon, had an impact on the reliability of the obtained results. For such reason, the results of the simulations are split in two for both vehicle categories.
- The slope profile had to be filtered appropriately to remove all the inconsistent values caused by the indirect calculation. In some cases, due to the fact that the speed was not

always recorded following the 5 seconds time-step, the absolute value of the slope calculated was too high and had to be neglected before launching the simulation. This resulted in a slight discrepancy of the distance travelled according to the two profiles. Since the speed profile had a much higher level of detail, the distance travel retrieved from it was assumed as the final one, equal to 124 km.

- The ancillaries consumption, which includes for example the electric system (lights, sensors, etc.), the power-assisted steering and the cooling system (which is a very important source of consumption for BEVs) was assumed to be around 9% of the overall consumption. This is in line with the fact that, thanks to the warm temperature, the AC should not be turned on for the entire day, and the main consuming component will be the cooling system, that controls the battery temperature to avoid the effects introduced in the previous chapter
- The loading conditions, as introduced before, were assumed since there was no information coming from the tested diesel van. For both 3.5 tons and 5 tons versions the weight was assumed to be decreasing linearly along the whole duration of Path 1 and Path 2. This additional deficit makes the simulated scenario even more challenging for BEVs, in line with the objective of identifying a potential limit of the electric van
- Finally, the software has a time-step of 1 second, compared to the 5 seconds of the recording device. Because of this, the simulation results are much more detailed, in fact the resulting matrix is composed of 33,712 values for each variable. A side effect of this increased level of detail is that the overall distance simulated is 56% greater than the one of the diesel van. In fact, Path 1 and 2 are respectively 97.3 km and 96.8 km long, giving a total distance travelled of 194.1 km compared to 124 km of the original test.

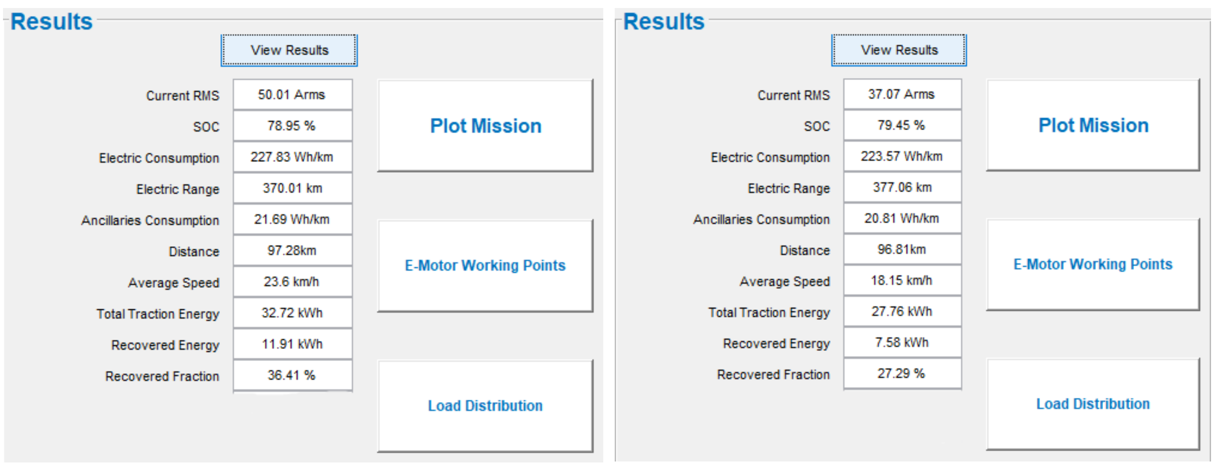


Fig. 28 Simulation summary output of Path 1 (left) and Path 2 (right) for the 3.5 tons Daily electric

This is one more deficit for the BEV and one more confirmation that the simulation represents the worst-case scenario (although there is still the potential effect of extreme temperature that will be analysed later on).

In addition to the variables' matrix, the simulation generates a summary of the final values of the same variables, which is shown for the 3.5 tons vehicle in figure 28. The same table for the 5 tons version is attached in Exhibit 21. Starting from the bottom, the Path 1 has a much higher fraction of recovered energy, which is calculated as % of the consumed energy that is recovered thanks to regenerative breaking. This means for example that, for Path 1, the final SoC if the regenerative breaking was missing would be 71.29 %, almost 8% lower than the simulated value. This reflects the expectation that Path 1 would be ideal for a BEV, which was derived from the high fluctuations of the original speed and slope profiles. Nonetheless, Path 1 is much more consuming, since even with a much higher recovered fraction of the consumed energy, the final SoC is lower. By combining the two paths, the remaining SoC of the 3.5 tons van is 58.4 %, while the 5 tons version reaches a lower peak of 38.2% and stabilizes in the end at 40%.

The same behaviour can be observed in the current rms (root mean square) profile in fig. 29. All the positive values correspond to battery discharges, meaning current flowing from the battery towards the electric motors. On the other side, the negative values represent energy flowing from the regenerative braking system towards the battery. The portion of the graph that

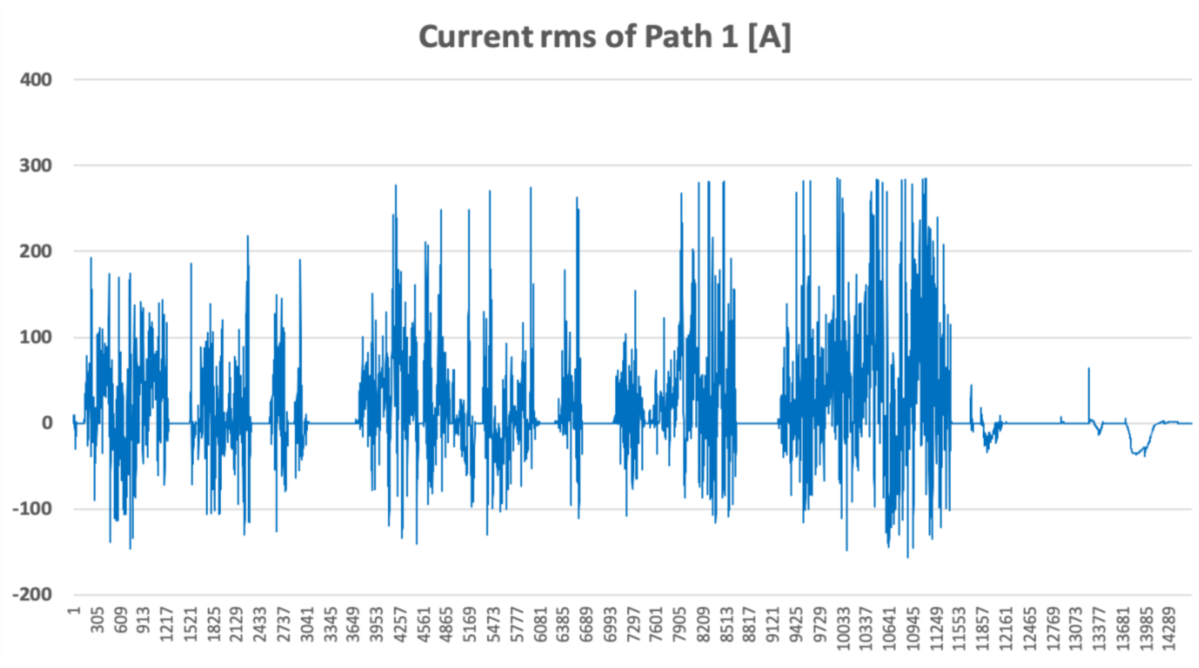


Fig. 29 Battery current root mean square of Path 1 for the Daily electric 3.5 tons

is below the 0 mark explains the outstanding 36% of recovered energy in Path 1. The same trend is also observed in the Daily electric 5 tons, in exhibit 20, with slightly higher values since the electric motor require more energy to move the higher GVW and are also more powerful (80 kW compared to the 60 kW motor of the 3.5 tons version). The energy fraction recovered by the 5 tons version is the same of the 3.5 tons van, since the consumed energy is much higher, although the absolute value is almost 40% greater, due to the increased weight (the otherwise dissipated energy in the braking system is proportional to the GVW of the vehicle).

Finally, the most important output of the simulation is the SoC (State-of-Charge) of the battery, since from this parameter it is possible to understand whether the electric van is able to meet the business requirements. The first learning that can be derived from fig. 30 is the impact on the energy consumption of the GVW. This confirm the original assumption that, while for urban applications BEVs can be very competitive, for extra-urban MDVs the limitations of electric powertrains start to play a critical role. The gap between the two trends gets progressively bigger and at the end of the simulation the 5 tons van has a SoC that is almost 20% lower than the one of the 3.5 tons variant. That being said, the results still go beyond expectations, since in both cases the final SoC is high enough to cover potential variations of the mission profile.

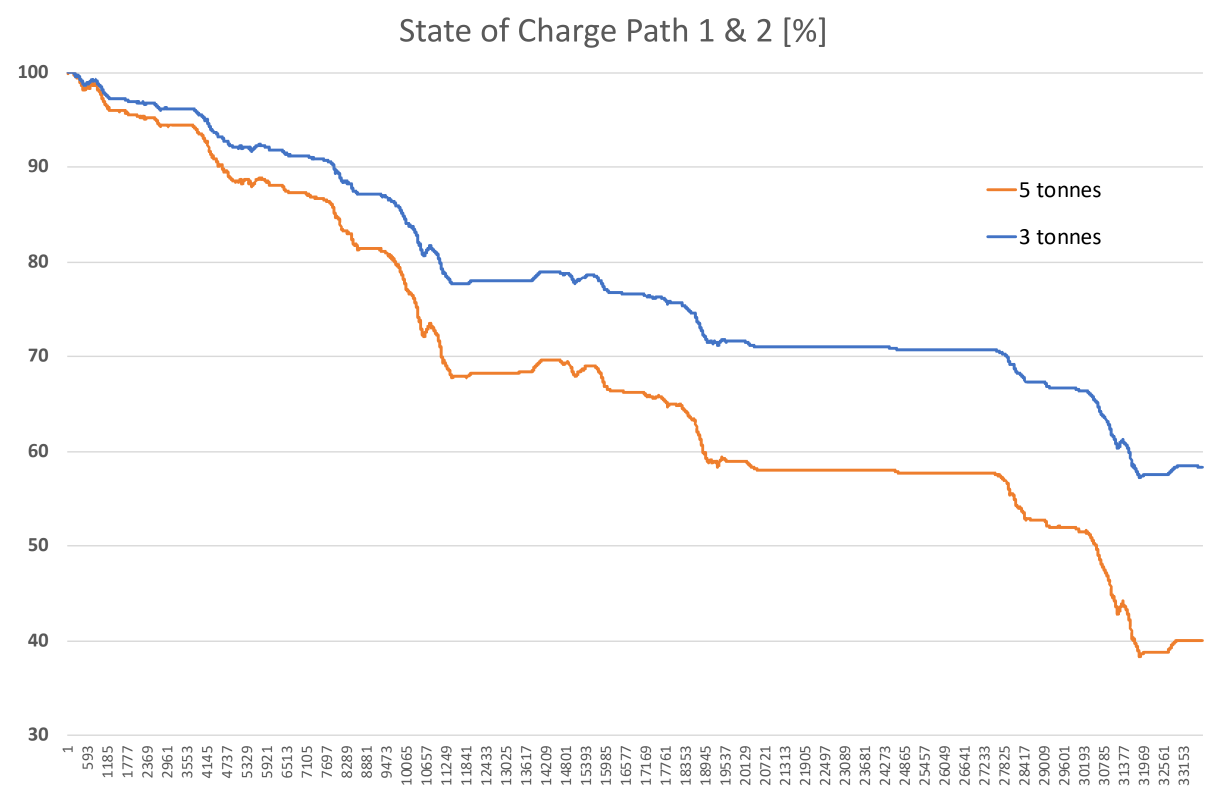


Fig. 30 Battery current root mean square of Path 1 for the Daily electric 3.5 tons

The simulated Iveco Daily electric has a battery capacity of 91 kWh, sold at a price of around 145,000 €, in a three battery configuration, while there are also two other versions, in single and double battery configurations. The three battery version can achieve, from the simulations' results, a range of 470 km for the 3.5 tons van and 370 km in the 5 tons variant. On the other side, from the SoC the vehicle's range that can be obtained from the travelled distance, 194.1 km, and the final charge level of the battery, is different from the one just calculated. For the 3.5 tons version it is around 462 km while for the 5 tons van it is 323.5 km. Once more, depending on the driving cycle, the weight can play a decisive role on the business viability of BEV.

Even though the SoC graph clearly shows that for this particular mission the electric van is able withstand the daily routine, a sensitivity analysis is needed to come to a proper judgement. In fact, while this simulation represents a worst-case scenario under the given conditions, by removing any assumptions things may change drastically. For example, in case no long stops are made during the day, such as the 1 hour 40 minutes break of the test mission, the BEV battery could overheat, leading to increased consumption (due to lower efficiency), or even the need to completely stop the van to cool down the battery pack. A second impactful assumption is the loading condition of the vehicle. In case the weight of the vehicle does not reduce progressively over time, for example for all those applications in which heavy equipment need to be carried around from one destination to another, the final SoC could be dramatically lower, even cross the zero mark before the end of the day. In fact, Path 2 resulted to be slightly less burdensome compared to Path 1 thanks to the fact that the load of the van is much higher during the first part of the morning. By loading the Daily electric with the same weight of Path 1, it can be expected that the SoC at the end of Path 2 for the 5 tons variant gets much closer to 30%, or even cross that mark. Keeping in mind that a certain battery level needs to always be kept as a reserve in case of emergency, in that case the viability of a 5 tons BEV is again uncertain. Lastly, the most impactful condition that was left out of the simulation is the weather. In the test case the temperature was relatively warm, but as stated in the introduction of this chapter, extreme temperatures can have a massive impact on the battery performance. If the assumption of 40% reduction of the range, which was introduced during the assessment of heat pumps for EVs, this would mean 40% less capacity of the battery, meaning that the 5 tons van would run out of battery before the end of the day. Even the 3 tons Daily electric would have a final SoC below 20%, which would not always guarantee a safe return to the central hub in case of extra-urban applications such as the simulated one. Relying on public charging stations can be too risky for business applications, due to the early development stage of the charging infrastructure. In most European countries, as it can be seen in exhibit 23, there are more than 10 EVs per slow charging station in urban areas. Even for fast charging, which would be the ideal solution for commercial vehicles, the density of charging stations is not yet enough to cover all needs. Albeit in most European countries there is more than one fast charging station every 60 km of highways, this is a national average, considering that such charging points will be concentrated around metropolitan areas and on high traffic roads. Commercial vehicles many times need to service remote areas where no charging stations will be available within a range of 30 to 50 kilometres. Furthermore, considering that the Iveco Daily electric 5 tons, in the 3-battery version, costs more than 115,000 € (around 2 times the price considered in the economic analysis), an additional investment in charging stations would be unrealistic for any SME[13]. On the other side, having alternative generators on-board, such as small conventional diesel generators, or fuel-cells, to cover emergencies, it would also be too expensive for such applications. Overall, unless certain conditions are met, commercial electric MDVs are still not a reliable solution. Further technology advancements will still be needed to both reduce the weight of the battery pack (by increasing the energy density of the cells) and increase at the same time the capacity, to cover all possible daily needs.

13 SME = Small to Mid-size Enterprise

7 CONCLUSION

The initial objective of this thesis was double:

- To understand whether BEVs are economically viable for urban applications, in which the vehicle is still able to satisfy the business needs even considering the limits of the current state of the art technology. The economic model was built around the urban logistics and delivery business, characterised by a limited range needed, the possibility to charge between one trip and the successive at a central hub and tackle the increased ICE consumption in high-traffic urban conditions.
- Assess whether BEVs are competitive, in terms of performance, even in more demanding applications, where the range limit of the vehicles and/or the increased weight due to the battery can be a constraint for business applications. To do so, real life data of a diesel vehicle was gathered and used as the input of a software that simulates the corresponding BEV performance.

The economic results obtained partially confirm the initial hypothesis of the existence of an application, in which the TCO cost parity has already been achieved by BEVs. Although some initial assumptions needed appropriate corrections to better reflect real conditions, the original case presents a very interesting application and it is expected to reach the widespread adoption phase in the next 2-3 years. The research highlighted how the real barrier to the implementation of BEVs is the range, rather than the weight. Given this achievement, the scope of the analysis was limited to LCVs and regional MDVs, for which the size of the battery doesn't have significant impacts on the efficiency of the vehicle, thanks to its limited weight. Consequently, a battery size was defined to match the business requirements of urban logistics providers. Finally, it was determined that the final customer would incur in upfront additional costs of about 15,500 €, which would be compensated by lower operating costs in 3-5 years maximum, depending on whether congestion charges are considered or not. This result would be achieved only in case the widespread adoption of commercial EVs will trigger economies of scale in the production of such vehicles. Otherwise, as it happens currently, such vehicles are produced in small batches, with variations of the production line and throughput time, which explain the much higher purchase price.

Secondly, the operational limits of battery electric vehicles were assessed following a structured research method, which is represented in fig. 31. First of all, a more demanding scope was

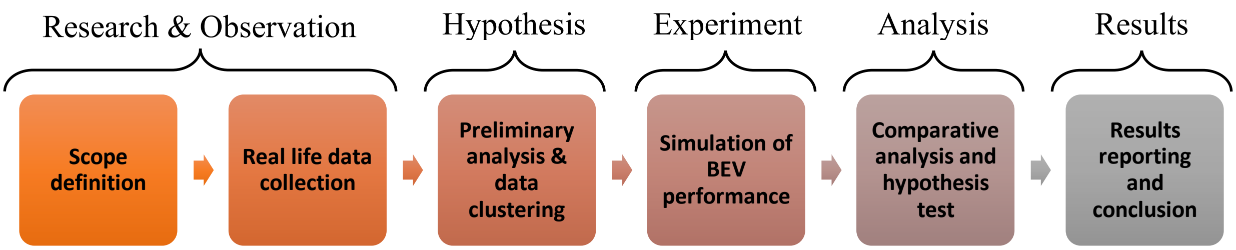


Fig. 31 Battery electric vehicles' operational limits research method

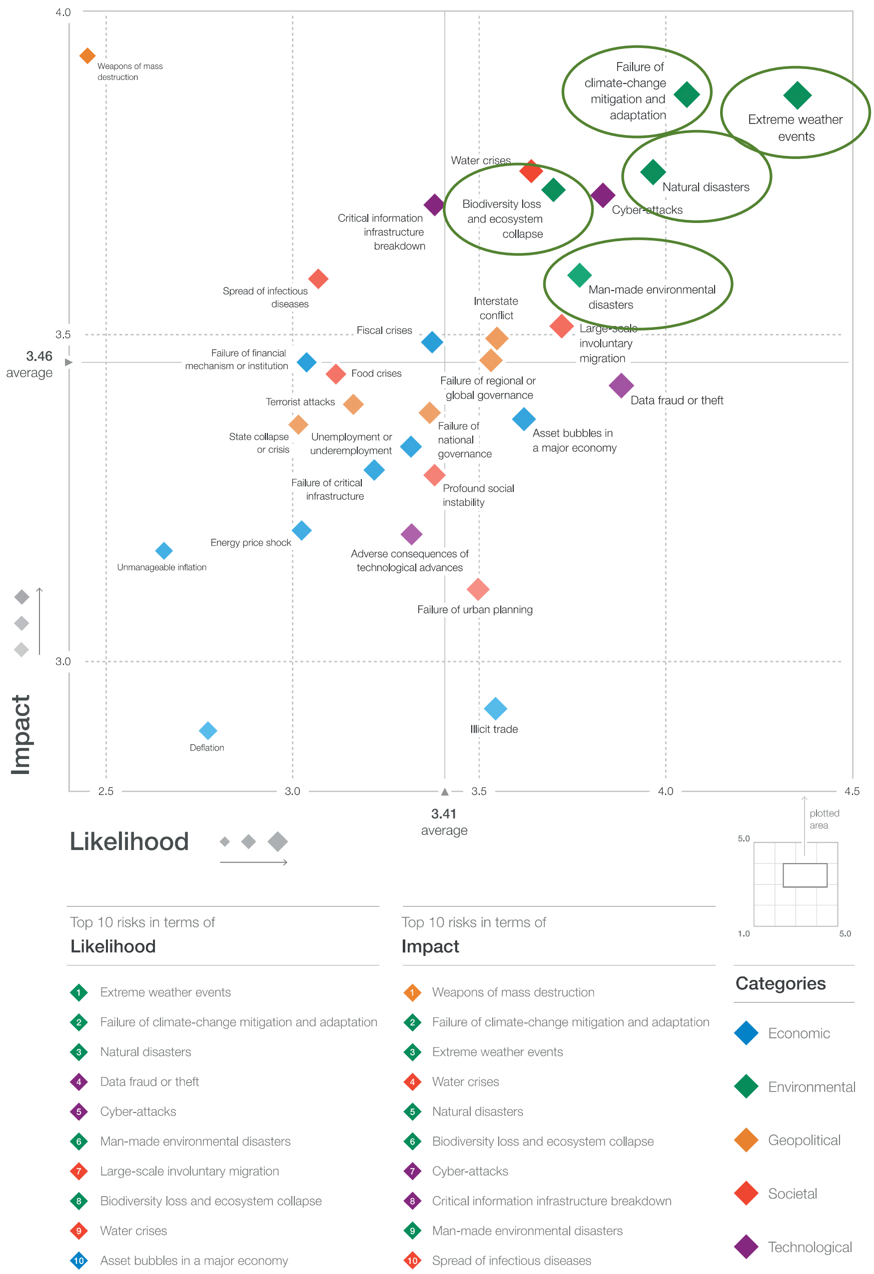
defined together with an IoT company, WAY s.r.l., specialised in the localization and management of moving vehicles. In particular, within the available portfolio of clients, a company working in the installation and maintenance of communication networks was selected. This business requires LCVs to travel longer daily routes, compared to urban applications, and the selected vehicle was operating in a area full of hills, adding one extra challenge to BEVs. The data collected was used to formulate the initial hypothesis that, for this specific application, BEVs would not be adequate to carry out daily operations. This postulate was justified by the fact that, as part of the inputs needed by the simulation tool, a more demanding load condition (compared to the real-life diesel vehicle) was set. By using an Iveco simulation software, the performance of the analogous electric version of the same vehicle tested was generated. The results proved that the original assumption was wrong, since under the simulation condition, the electric van completed the daily route with 58% remaining battery capacity for the 3.5 tons version and 40% for the 5 tons van. Nonetheless, in case part of the initial conditions are removed, in particular the warm temperature and a progressively reducing load, BEVs will not always satisfy the business needs.

For applications that require LCVs and MDVs (here considered up to 5 tons) to travel less than 200-250 km a day in sub-tropical areas, battery electric vehicles are already a viable solution, both economically and operationally. The viability of such solution extends also to the Mediterranean part of Europe, where temperatures rarely go below zero. For all applications in which extreme temperatures (can be hot and/or cold) are frequent during business periods, the viability of BEVs must be carefully assessed before incurring in considerable investments. Nonetheless, it is recognised that battery electric and fuel cell vehicles (which is a technology that is currently less developed, although promising for long range and heavy-duty applications) are the only solution to meet the Paris Agreement targets. Thanks to the commitment and investments of countries such as Norway and The Netherland (pioneers in the promotion of electric vehicles despite the non-optimal climate conditions), positivity is growing around this technology. Most OEMs have foreseen the need of converting their current portfolio of vehicles and are investing hundreds of millions in the launch of new BEVs and in R&D activities around the battery technology. From my personal experience in the launch of an urban SUV and an LCV within Toyota, I am confident that future technological breakthrough will allow electric vehicles to achieve mass adoption. The expected increased energy density and lower cost of production of solid-state batteries is likely to make this technology competitive in all road vehicle applications, potentially even for heavy trucks. Furthermore, such technology claims to be 100% recyclable, answering to the current discussions around the full-cycle emissions of lithium-ion battery electric vehicles. I believe that in the next 5 to 10 years it will be possible to switch to mobility solutions which have zero life-cycle emissions, for both private and business applications, and a full conversion of the worldwide vehicle fleet might be completed before 2050.

8 ANNEXES

Exhibit 1

The Global Risks Landscapes 2019 (source: WEF, 2019)



Source: World Economic Forum Global Risks Perception Survey 2018–2019.
Note: Survey respondents were asked to assess the likelihood of the individual global risk on a scale of 1 to 5, 1 representing a risk that is very unlikely to happen and 5 a risk that is very likely to occur. They also assess the impact on each global risk on a scale of 1 to 5 (1: minimal impact, 2: minor impact, 3: moderate impact, 4: severe impact and 5: catastrophic impact). See Appendix B for more details. To ensure legibility, the names of the global risks are abbreviated; see Appendix A for the full name and description.

Exhibit 2

Main differences between the NEDC and WLTP test cycles (source: https://wltpfacts.eu/)

	NEDC	WLTP
Test cycle	Single test cycle	Dynamic cycle more representative of real driving
Cycle time	20 minutes	30 minutes
Cycle distance	11 kilometre	23.25 kilometre
Driving phases	2 phases, 66% urban and 34% non-urban driving	4 more dynamic phases, 52% urban and 48% non-urban
Average speed	34 kilometre per hour	46.5 kilometre per hour
Maximum speed	120 kilometre per hour	131 kilometre per hour
Influence of optional equipment	Impact on CO2 and fuel performance not considered under NEDC	Additional features (which can differ per car) are taken into account
Gear shifts	Vehicles have fixed gear shift points	Different gear shift points for each vehicle
Test temperatures	Measurements at 20-30°C	Measurements at 23°C, CO2 values corrected to 14°C

Exhibit 3

Direct CO2 emissions from the transport sector under different reduction scenarios for the period 2020 to 2050 (source: Delgado & Rodríguez, 2018)

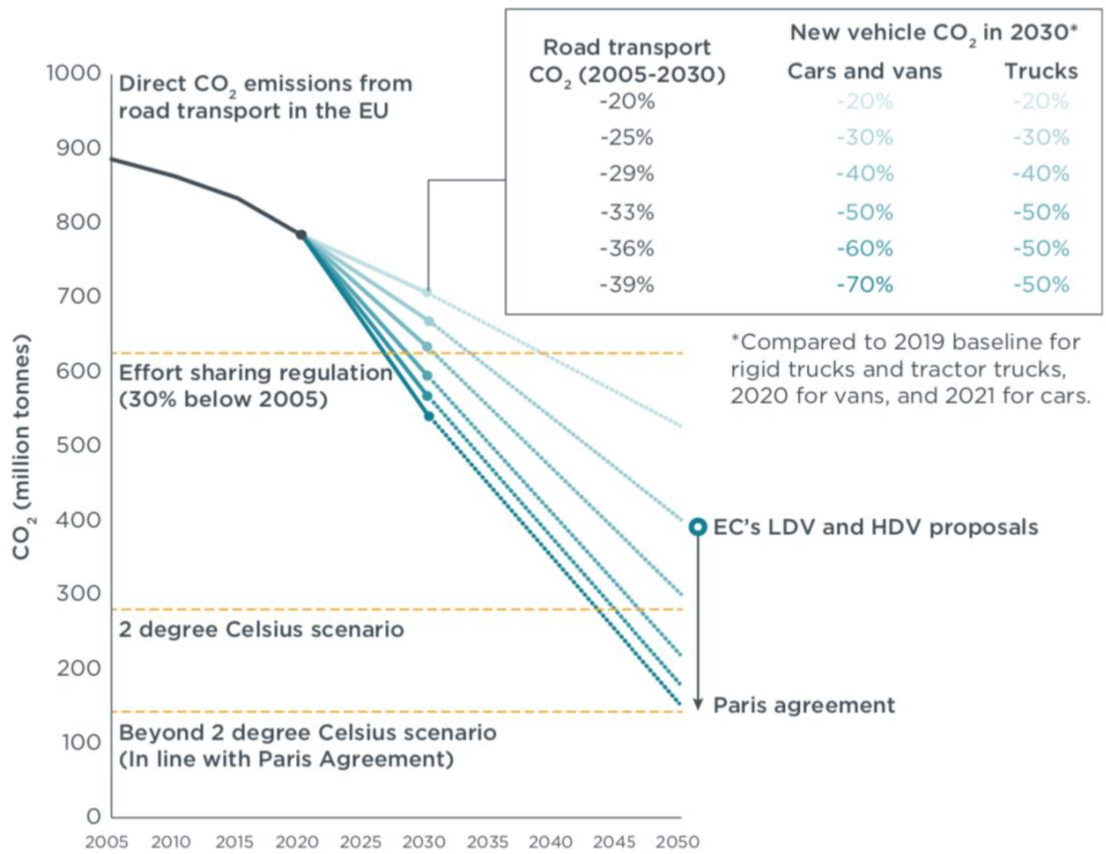


Exhibit 4

Comparison of global CO2 regulations for new passenger cars (source: Mock P., 2019),

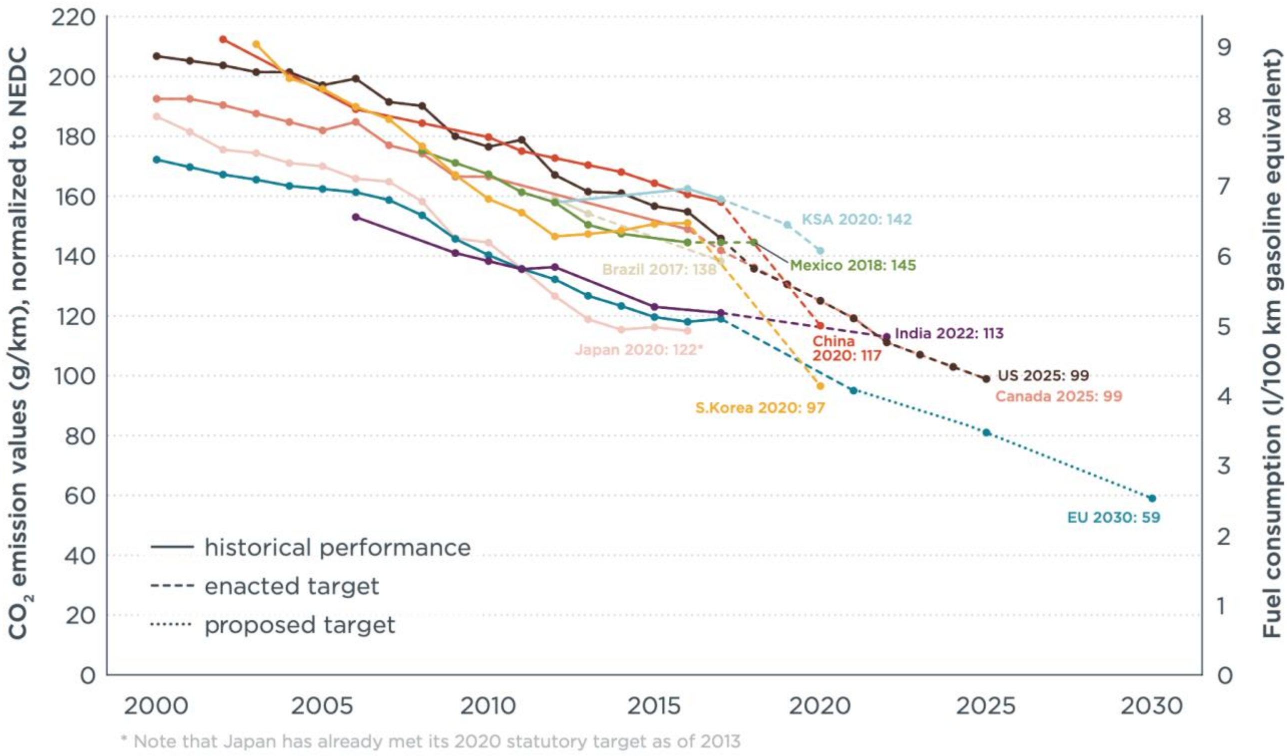


Exhibit 5

Electric vehicle policy goals, targets and announcements, 2020-50 (source: Lutsey N., 2018)

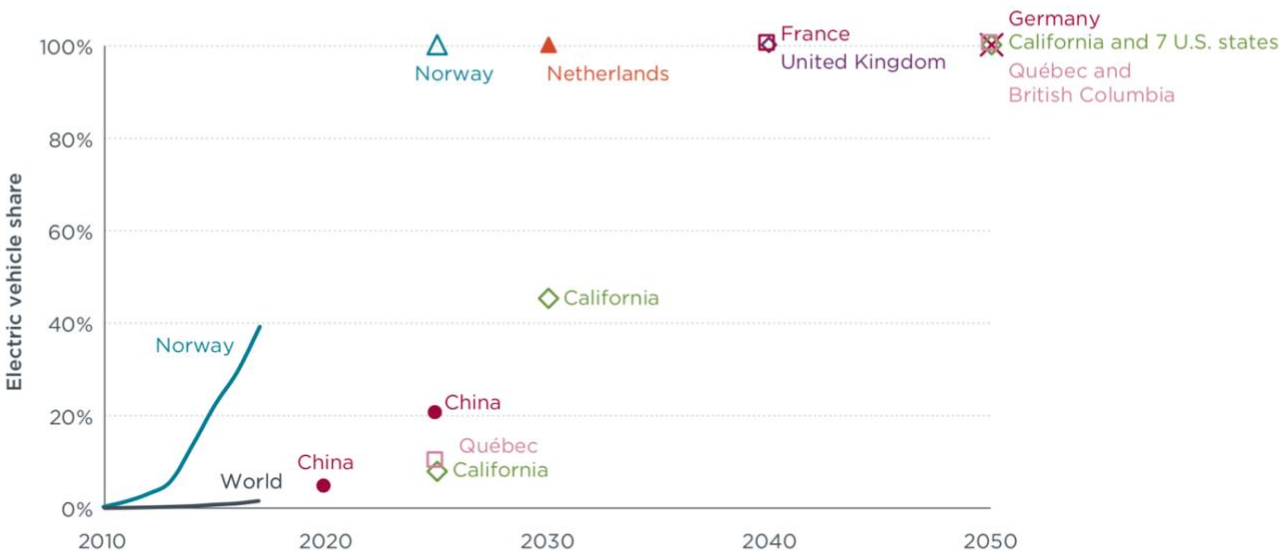


Exhibit 6

Distribution of total ETS and non-ETS direct CO2 emissions in the European Union in 2015 (source: Delgado & Rodríguez, 2018), GtCO2: gigatons of carbon dioxide

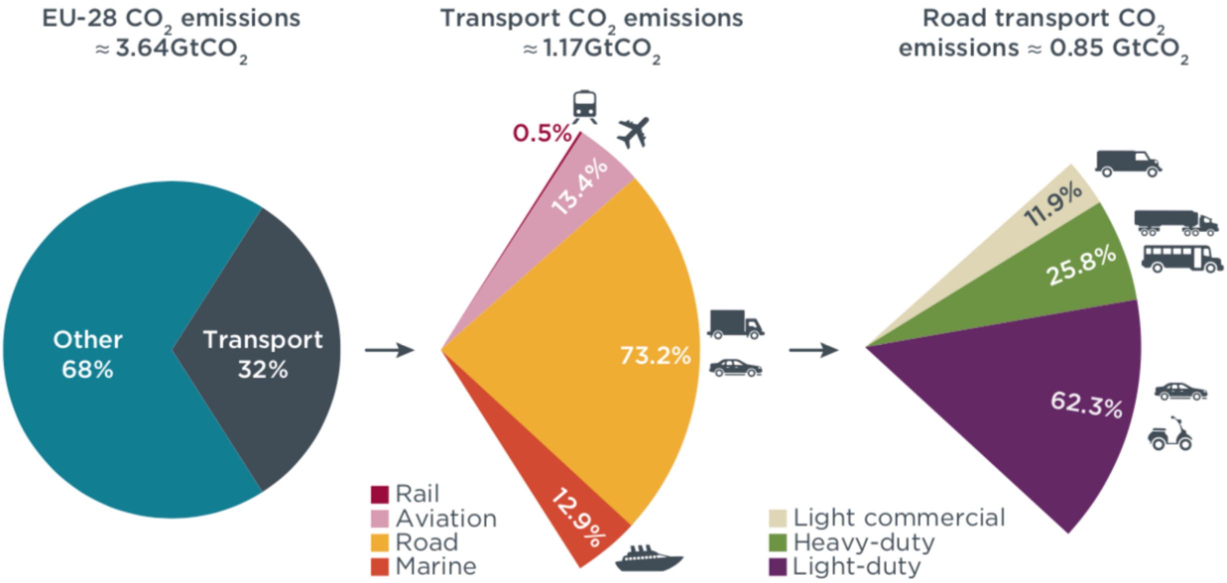


Exhibit 7

Heavy-duty vehicle classification for the purpose of CO2 emissions and fuel consumption certification in the EU (source: Rodríguez. 2018)

Axle type	Chassis configuration	Gross vehicle weight (tonnes)	Vehicle Groups	Date of certification requirement
4x2	Rigid	>3.5 – <7.5	0	Not considered by the certification regulation
	Rigid (or tractor)	7.5 – 10	1	January 1, 2020 for all new registrations.
	Rigid (or tractor)	>10 – 12	2	
	Rigid (or tractor)	>12 – 16	3	
	Rigid	>16	4	January 1, 2019 for new produced vehicles. July 1, 2019 for all new registrations.
	Tractor	>16	5	
4x4	Rigid	7.5 – 16	6	Not considered by the certification regulation
	Rigid	>16	7	
	Tractor	>16	8	
6x2	Rigid	all weights	9	January 1, 2019 for new produced vehicles. July 1, 2019 for all new registrations.
	Tractor	all weights	10	
6x4	Rigid	all weights	11	July 1, 2020 for new registrations.
	Tractor	all weights	12	
6x6	Rigid	all weights	13	Not considered by the certification regulation
	Tractor	all weights	14	
8x2	Rigid	all weights	15	
8x4	Rigid	all weights	16	July 1, 2020 for new registrations.
8x6 8x8	Rigid	all weights	17	Not considered by the certification regulation

Exhibit 8

Summary of key elements of the HDV CO2 standards proposal for the EU (source: Rodríguez, 2018)

Policy option	Key elements
Scope	• The regulation applies to vehicles belonging to **groups 4, 5, 9, and 10** as defined in the certification regulation (see Table 1). • Vehicles that are not intended for the delivery of goods are deemed to be *vocational vehicles* and are exempted from the regulation. The designation of a truck as a vocational vehicle is under the discretion of the manufacturer.
Metric	• The average specific CO_2 emissions are measured in grams of CO_2 per tonne-kilometer (**gCO_2/t-km)**. • Compliance with the standards is determined by comparing the average specific CO_2 emissions of a manufacturer's fleet against the manufacturer-specific CO_2 targets mandated by the standard. • The manufacturer's average specific emissions are a function of the CO_2 emissions of each new HDV and of the registration share in each vehicle sub-group.
Baseline	• For each vehicle sub-group, the reference CO_2 emissions are determined based on the monitored and reported data of the year 2019 for the complete EU. The reference emissions of each sub-group are common to all manufacturers.
Targets and timeline	• The CO_2 reduction targets for each sub-group are set relative to the baseline CO_2 emissions of the year 2019. • The proposal sets a mandatory reduction of **15%** relative to the 2019 baseline, in the **2025 to 2029** time period. • The proposal sets a mandatory reduction of at least **30%** relative to the 2019 baseline from **2030 onwards**. This reduction target is to be reviewed by 2022. • The numerical value of the resulting targets, in gCO_2/t-km, is specific to each manufacturer and is dependent on its fleet composition.
ZEV/LEV incentives	• Each zero-emission vehicle (ZEV) is certified with 0 gCO_2/km and is counted as 2 vehicles, referred to as a **super-credit multiplier of 2**, for the purpose of determining a manufacturer's average emissions. Low-emission vehicles (LEVs) are defined as those emitting less than 350 gCO_2/km (about half of the average of the fleet emissions) and are counted as up to 2 vehicles depending on their tailpipe CO_2 emissions. • The super-credit scheme is also extended to heavy-duty ZEVs in vehicle groups outside of the scope of the CO_2 standards. ZEV super-credits outside of the regulated categories can only reduce the average specific emissions of a manufacturer up to 1.5%. • Total ZEV and LEV super-credits can only reduce the average specific emissions of a manufacturer by a **maximum of 3%.**
Flexibilities	• From 2019 to 2024, manufacturers can accumulate early-credits that can only be used for compliance in 2025. The **early-credits** are calculated against a linear trajectory between the baseline and the 2025 targets. • In the period 2025 to 2028, manufacturers are allowed to accumulate credits and debt. The credit/debt calculation is done **against a linear CO_2 reduction trajectory between the 2025 and 2030 targets**. • **Emissions debts must be cleared by 2029**. Emissions credits cannot be carried over for compliance from 2030 onwards. • At any given time, the total **debt of a manufacturer cannot be higher than 5%** its 2025 target multiplied by the respective number of vehicles. • Credits and debts are **not transferable** between manufacturers
Penalties	• Manufacturers are required to pay a per-vehicle penalty of **6,800 Euros for each gCO_2/t-km of excess emissions**. • In the period 2025 to 2029, the excess emissions calculation takes into account the credits and debts accumulated in the previous years.

Exhibit 9

Implementation timeline of heavy-duty emissions standards in major vehicle markets (source: Yang & He, 2018)

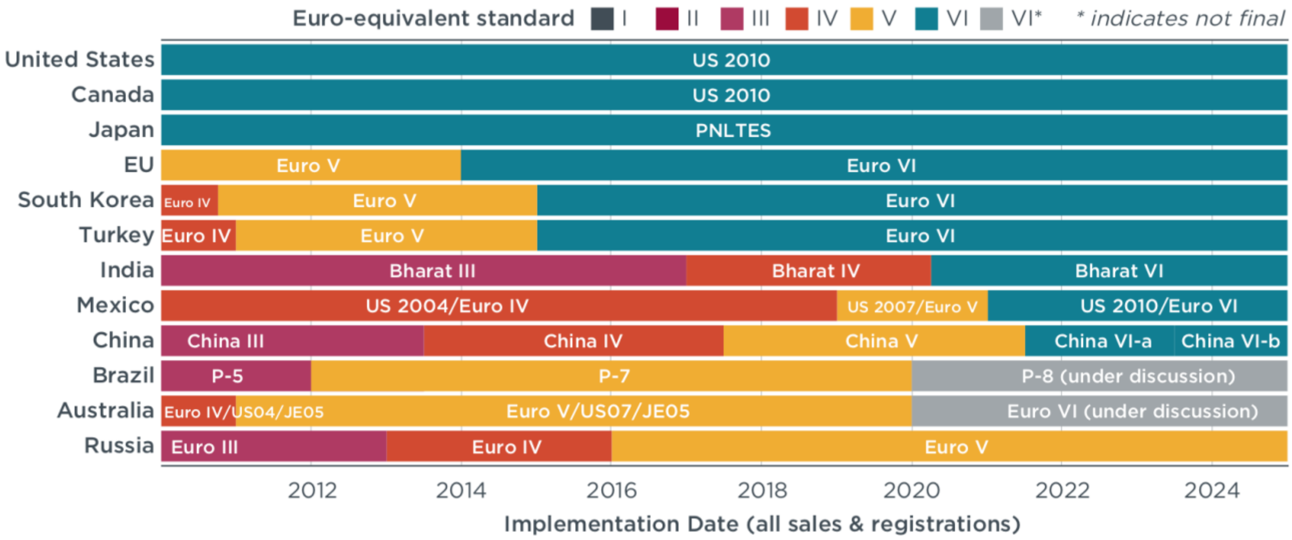


Exhibit 10

Commercial medium-duty zero emission vehicles in development or production in 2018 (source: Moultak et al., 2017)

				Technology Specifications									
Company	Name	Technology	Current Status	Range (km)	Battery Chemistry	Max Speed (km/hr)	Recharge Time/ Refuel Time	Torque (Nm)	Power output (kW)	Battery kWh (or Hydrogen Storage kg)	Vehicle Gross Weight (ton)	Load Capacity (ton)	Source
BYD	T5	Electric Class 5 truck	Production	250	FePO4	97	1.5 h	550	150	145	7.3	3.8	BYD (2016b)
BYD	T7	Electric Class 6 truck	Production	200	FePO4	90	1.75 h	550	150	175	11	5.9	BYD (2016c)
Daimler	eCanter	All-electric light-duty truck	Small-scale production	>100	Li-Ion		7 h (1 h = 80%)	380	185	70	7.5	4.6	Daimler (2016c)
Daimler Trucks	Canter E-CELL	All-electric light-duty truck	Replaced by the eCanter	>100	Li-Ion	90	7 h (1 h)	650	110	48.5	6	3	FUSO (2014)
Deutsche Post DHL Group	StreetScooter Work	Battery electric delivery truck	Production	50-80	Li-ion	120			48	20.4	2.1		Deutsche Post DHL Group (2016)
EFA-S	P80-E	Electric medium-duty delivery truck	Production	80-130	LI-FeYPO4	80	8-10 h	300	91	62	7.5	3.5	EFA-S (2010)
EMOSS	DYNA EV200	Battery electric	Production	160	LI-FeYPO4	85	8 h	700	120	62	7.5	4.6	EMOSS (2016)
EVI	EVI-MD	Battery electric medium-duty truck	Production	145	LiFeMgPO4	105	6-12 h	900	200	99	7.3-10		GreenFleet (2016)
Iveco	Electric Daily 5t	Battery electric delivery truck	Production	90-130	ZEBRA (NaNi/Cl2)	70		300	80	63.6	5	2	Deutsche Post DHL Group (2013)
Motiv Power Systems & Rockport		Electric delivery truck	Production	109-161		97	8 h (2-3 h 50%)	1,200	150	85/106/127	6.6	3.6	Motiv (2016a)
ORTEN & EFA-S	ORTEN E 75 AT	Electric medium-duty truck	Production	100	LiFePO4	80	4 h (22 kW)	1,150	90	72.5	7.5	3.6	ORTEN (2016)
Paneltex		Electric delivery truck	Production	200	LiFePO4					80-120	7.5-11		Paneltex (2017)
Renault	Maxity	Electric with hydrogen-powered fuel cell	Field test 2015	200		90		270	47/ 20	42/ 45	3.5	1	Renault Trucks (2015)
Smith	Edison	Battery electric (chassis cab)	Production (except U.S.)	90-160	Li-ion	80	6-8 h (4 h fast)		90	40	3.5-4.6	1.2-2.1	Smith (2011a)
Smith	Newton	Battery electric (chassis cab)	Production	65-160	Li-ion	80	8 h	600	120	40-120	6.4-12	2.8-7.6	Smith, (2011b, 2011c)
Spijkstaal	Ecotruck 7500	Electric garbage truck		70-100	Li-ion	40	6-8 h		20		7.5	3.7	Spijkstaal (2016)
US Hybrid	eCargo	Battery electric cargo truck	Production	120	Li-ion (18650)	104			120	36	4.5		US Hybrid (2016a)
US Hybrid	H2 Cargo	Fuel cell plug-in cargo truck	Production	200	Li-ion	97	<5 min		120	28 (9.8 kg)	6.4		US Hybrid (2016c)
Workhorse	E-Gen	Electric delivery with range extender		96 (145)		108		2,200	200	60	8.8		Workhorse (2016)

Exhibit 11

Light and medium-duty electric vehicle demonstration projects (source: Moultak et al., 2017)

Technology	Organization	Location	Time frame	Description	Source
Class 6 electric delivery trucks	Frito Lay	United States	2013	More than 250 Smith Newton electric delivery trucks. Project evaluates 10 of these delivery trucks to better understand the effectiveness of electric trucks in real-world applications.	Frito Lay, (2016); Prohaska, Ragatz, Simpson, & Kelly (2016)
Fuso Canter E-Cell/ Fuso eCanter	Daimler Trucks	Portugal	2014–2015	Eight vehicles used in trials for short-range delivery and inner-city transport.	FUSO (2015)
		Stuttgart, Germany	2016	Testing of five Fuso Carter E-Cell trucks by the parcel service provider Hermes.	Daimler (2016a,b)
Electric delivery vehicles for urban distribution	CWS, Boco, UPS, Smith Electric Vehicles, EFA-S, TCDi, Busch-Jaegen	North Rhine-Westphalia, Germany	2011–2015	A 2-year demonstration project that took data of 107,402 km driven by battery-powered electric trucks for urban distribution.	Stütz (2015)
Electric delivery trucks	Renault Trucks	Paris, France	2015	Testing of the all-electric D-range on delivery rounds of over 200 km with multiple battery recharge times during a 24-hour operating cycle.	Volvo Group (2015)
E-trucks—all electric trucks with refrigerated body	Renault Trucks	Switzerland	2016	Renault Trucks is testing two concept trucks that combined Renault's all-electric Midlum with an electric powered refrigerated body capable of carrying 3 metric tons of refrigerated products.	Volvo Group (2015)
Electric parcel and letter delivery trucks	German Post AG, StreetScooter GmbH, Langmatz GmbH, RWTH Aachen University, BMUB	Bonn, Germany	2012–2016	CO_2 GoGreen aimed to improve the vehicle technology, infrastructure technology, energy supply, and process design for using electric vehicles in parcel and letter delivery.	Appel (2013); BMUB (2016c)
Maxity electric delivery truck	Renault Trucks	France	2010	Pilot customers operated between 10 and 30 pre-production all electric trucks for deliveries.	Renault Trucks (2010)
Electric parcel delivery trucks	CalHEAT, California Energy Commission, Navistar, FCCC, Smith	Southern California	2012	Comprehensive performance evaluation of 3 E-Truck models using in-use data collection, on-road-testing, and chassis dynamometer testing.	Gallo & Tomić (2013)
Electric delivery truck	UPS, EVI	California	2013	UPS deployed 100 electric medium-duty delivery trucks to their California fleet, offsetting 126,000 gallons of conventional motor fuel per year.	EVI (2011); UPS (2017)
Electric delivery trucks	BAAQMD, CARB, San Francisco Goodwill, the Center for Transp. and Environment, BYD Corp.	Bay Area, California	2017	Goodwill is introducing 11 all-electric trucks to its truck fleet in 3 Californian counties, a $4.4 million project funded through California's cap-and-trade program, BAAQMD, and Goodwill.	CARB (2016a, 2016b)
Electric delivery trucks	SJVUAPCD, Motiv Power Systems, AmeriPride Services, CALSTART, First Priority Bus Sales	Central Valley, California	2016	Deployment of 20 zero-emission electric walk-in-vans and the necessary charging infrastructure for deliveries in the Central Valley, focused on disadvantaged communities. Funded through $7.1M grant from CARB, $5.8M from partners.	CARB (2016a, 2016b); SJVUAPCD (2016)
Electric parcel delivery truck	SJVAPCD, USPS, EDI, Motiv Power Systems, Morgan Olson, CALSTART, SunEdison	Stockton & Fresno, California	2016	Deployment of 15 all electric USPS "step vans" and the necessary charging infrastructure to form the basis of a USPS Advanced Vehicle Cluster. The project received $4.5M in California funds.	CARB (2016a, 2016b)
Electric delivery truck	UPS, H-GAC, CTE, US DOE, Workhorse Group	Houston-Galveston area, Texas	2015	Deployment of 18 all electric delivery trucks, estimated to avoid the consumption of 1.1 million gallons of diesel fuel over 20 years.	UPS (2015)
Electric delivery truck	UPS Limited	Feltham, UK	2017	Implementation of a smart charging system with energy storage to increase the number of vehicles that can be charged at a depot.	UK (2017)
Electric delivery vehicles	Gnewt Cargo	Southwark, UK	2017	Lease of 33 electric vehicles for last-mile logistics.	UK (2017)
Electric delivery truck	Nordresa, Purolator	Québec, Canada	2017	Purolator is testing of an all-electric delivery truck developed by Nordresa. The trials show electric trucks saving an average of 0.60 $CAN per kilometer resulting in profitable operation within 2 years.	AVEQ (2017)
Electric delivery truck	UPS, FREVUE	Rotterdam, Netherlands; London, UK	2014–2015	Deployed and tested 16 7.5-ton electrically retrofitted P80E Mercedes T2 in London and 4 in Rotterdam with charging infrastructure.	FREVUE (2017b, 2017c)
Electric logistics truck	FREVUE, Arup, Smith Newton, The Crown Estate, Clipper Logistics	London, UK	2014	Deployment of a 10-ton and 12-ton all electric Smith Newton to accommodate increased delivery volume from a depot to a consolidation center.	FREVUE (2017e)
Electric delivery trucks	UPS	Amsterdam, Netherlands	2013	UPS deployed 6 electric parcel delivery trucks in Amsterdam.	Netherlands Enterprise Agency (2016)

Exhibit 12

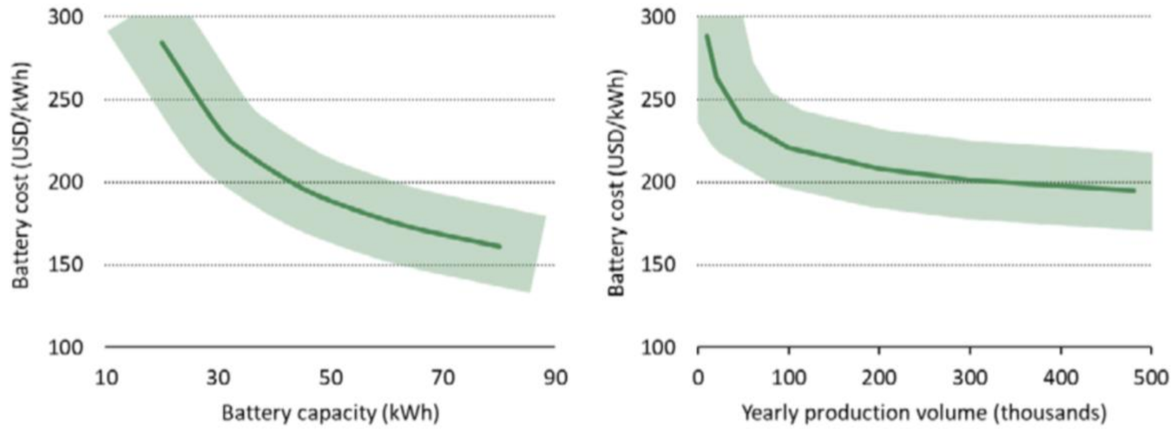
Sample of the main operational and announced Li-ion battery factories (source: IEA, 2018)

Country	Manufacturer	Production capacity (GWh/year)	Year of commissioning	Source
Operational				
China	BYD	8	2016	TL Ogan (2016)
United States	LG Chem	2.6	2013	BNEF (2018)
Japan	Panasonic	3.5	2017	BNEF (2018)
China	CATL	7	2016	BNEF (2018)
Announced				
Germany	TerraE	34	2028	TerraE (2017)
United States	Tesla	35	2018	Tesla (2018b)
India	Reliance	25	2022	Factor Daily (2017)
China	CATL	24	2020	Reuters (2017f)
Sweden	Northvolt	32	2023	Northvolt (2017)
Hungary	SK innovation	7.5	2020	SK innovation (2018)

Note: CATL = Contemporary Amperex Technology Limited.

Exhibit 13

Effects of changes in size and manufacturing volume on the battery cost (source: IEA, 2018)



Notes: Battery costs refer to a mid-sized car battery evaluated using the BatPaC model (Version 3.1) of the ANL. When not subject to sensitivity, the technical specifications for the battery are: power of 100 kW, capacity of 35 kWh, production volume of 100 000 packs per year and NMC 111-Graphite chemistry. The shaded area represents the 15% uncertainty associated with BatPaC's cost estimates.

Exhibit 14

Average cost of ownership of battery electric cars (source: Slovik & Lutsey, 2016)

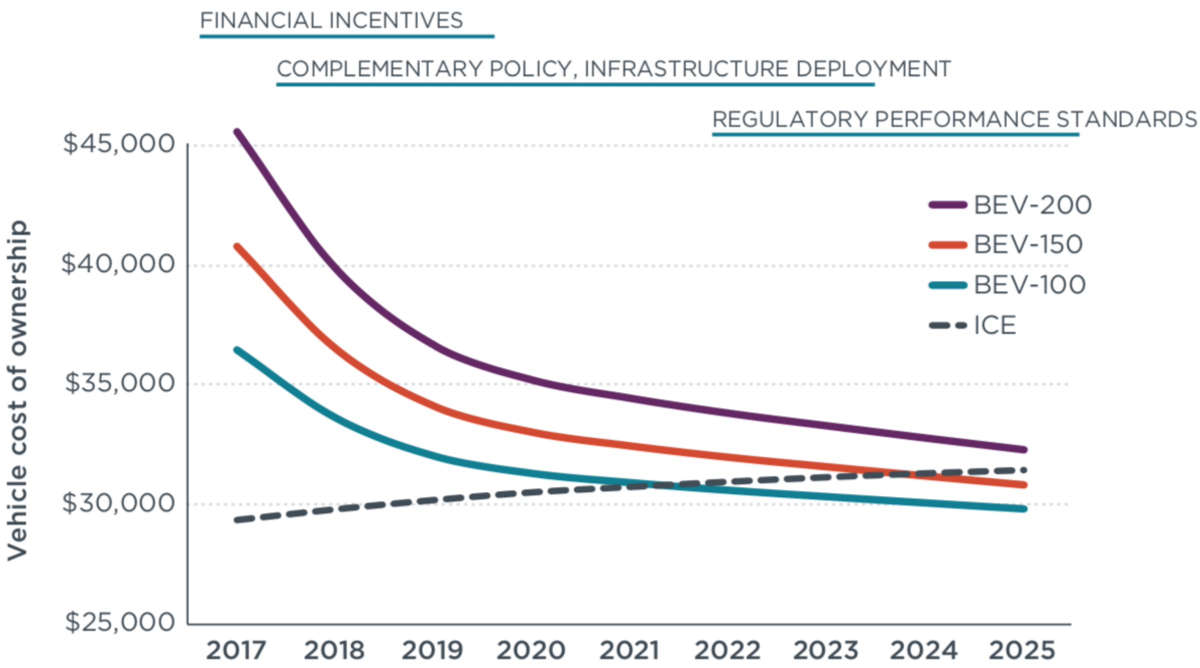


Exhibit 15

Congestion charges and urban access regulations in Europe

(source: https://urbanaccessregulations.eu/userhome/map)

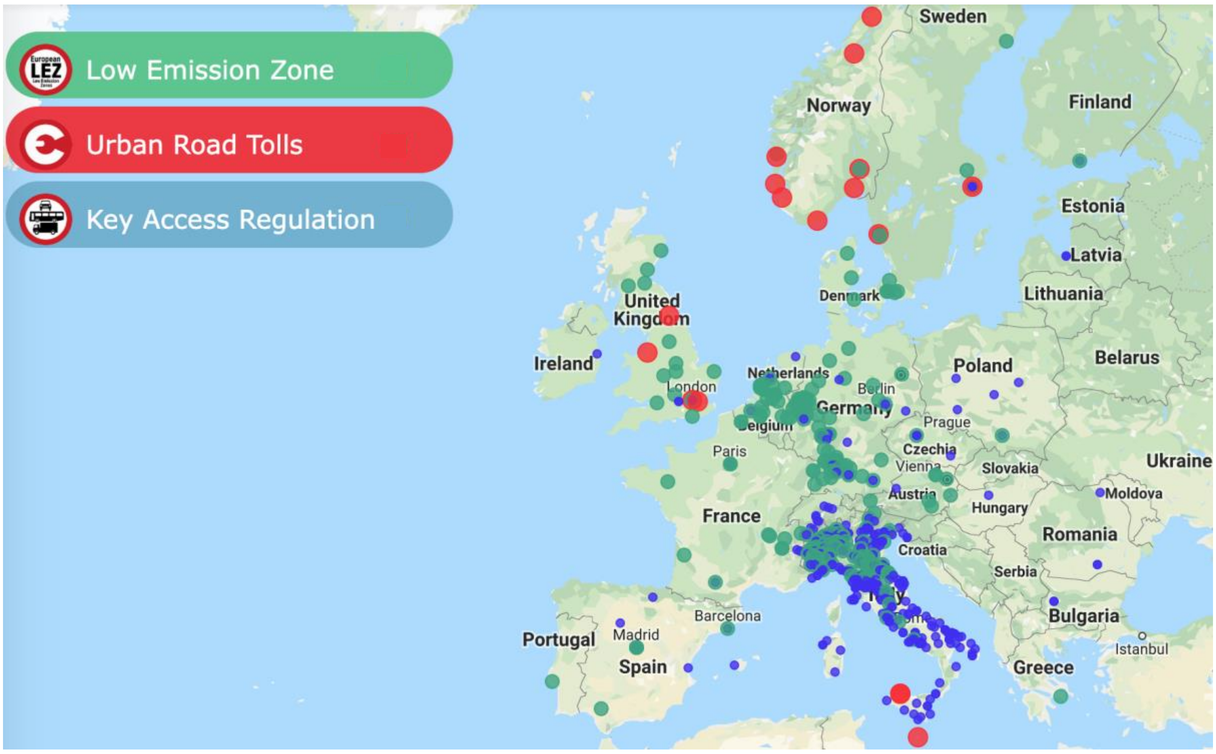


Exhibit 16

Timing of BEV TCO parity with diesel vehicles (source: Heid et al., 2017)

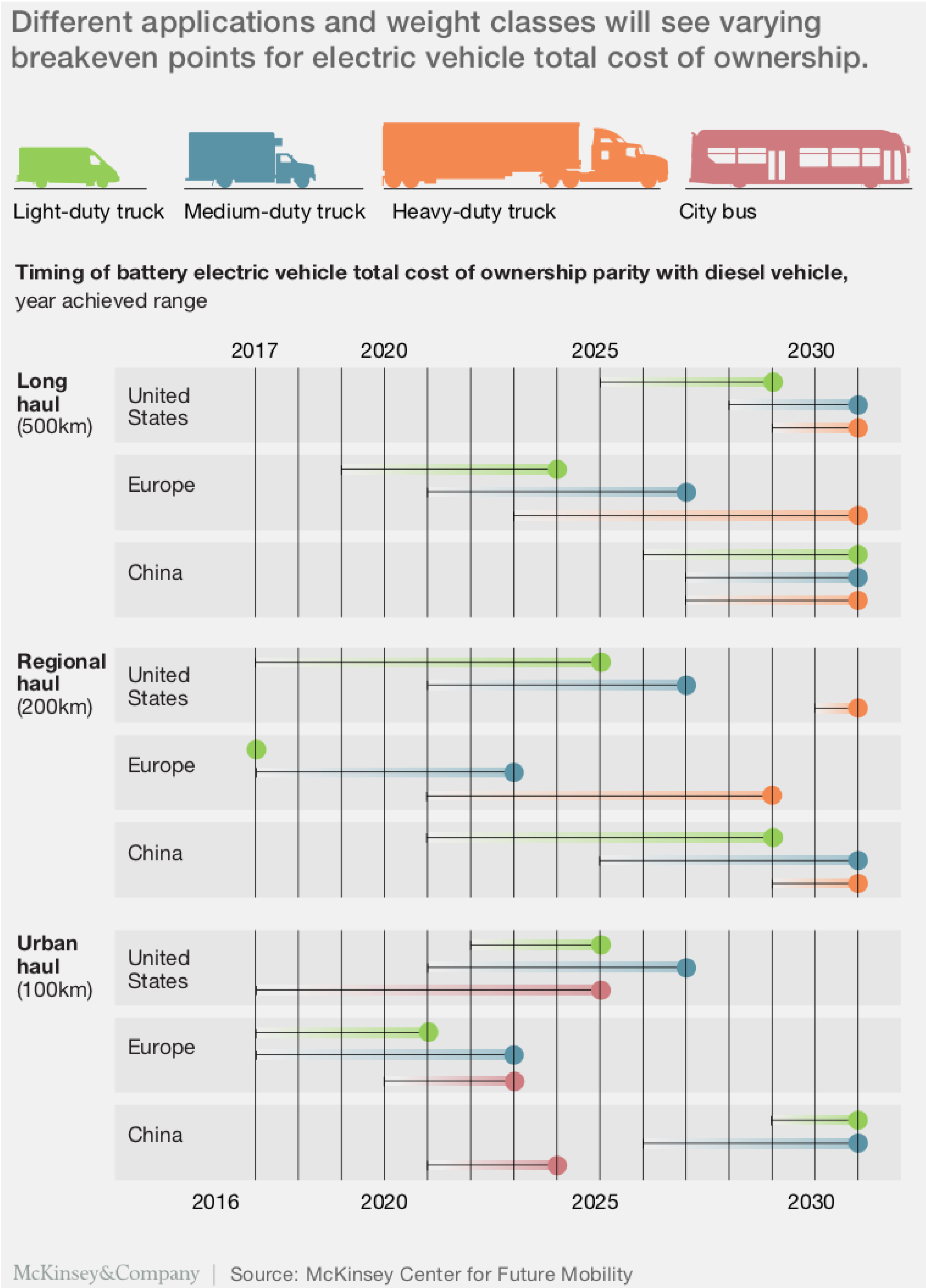


Exhibit 17

Regional light-duty truck hub-and-spoke delivery case (source: Heid et al., 2017)

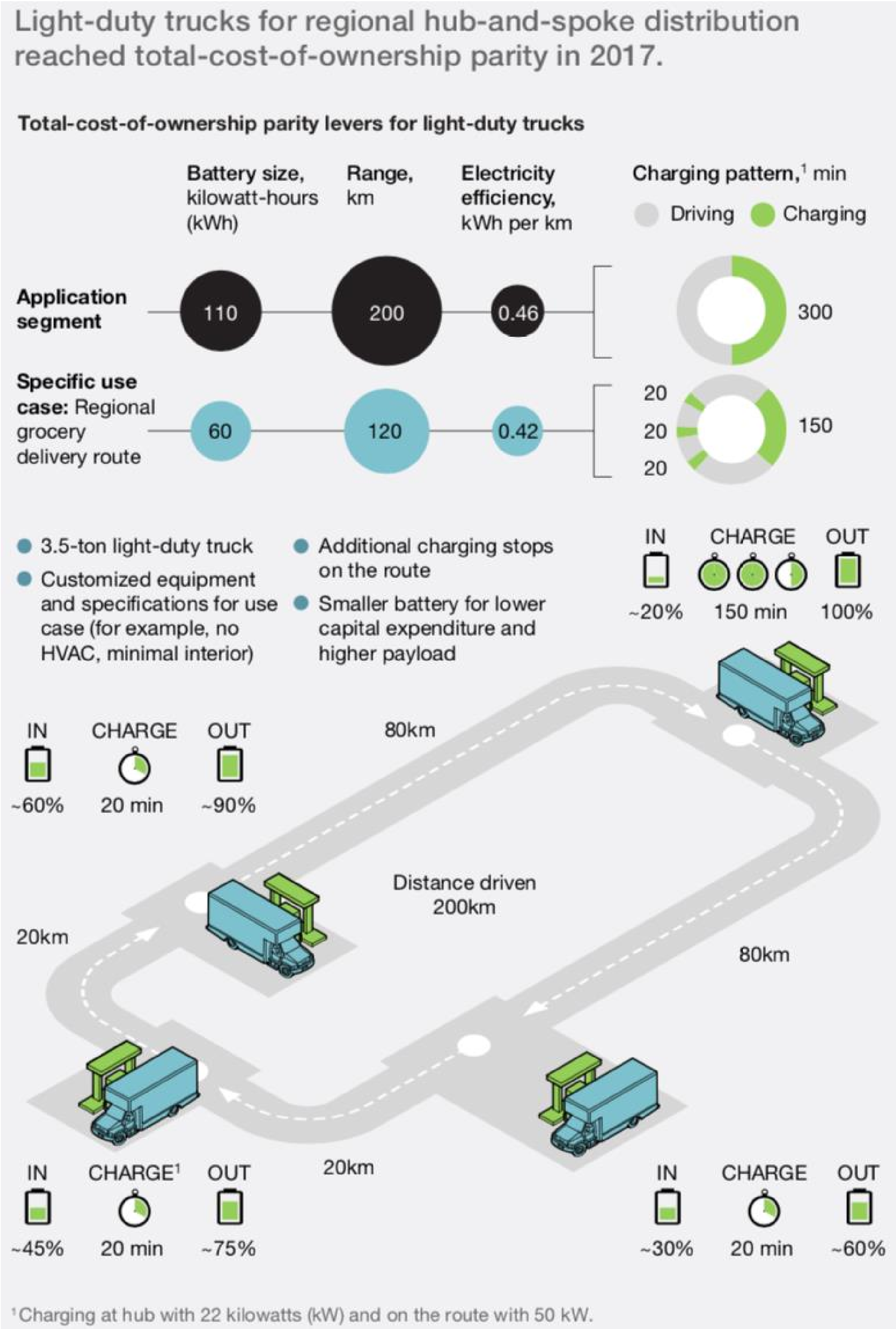


Exhibit 18

Illustration of categories and process of the heat generation within LIBs (source: Ma et al., 2018)

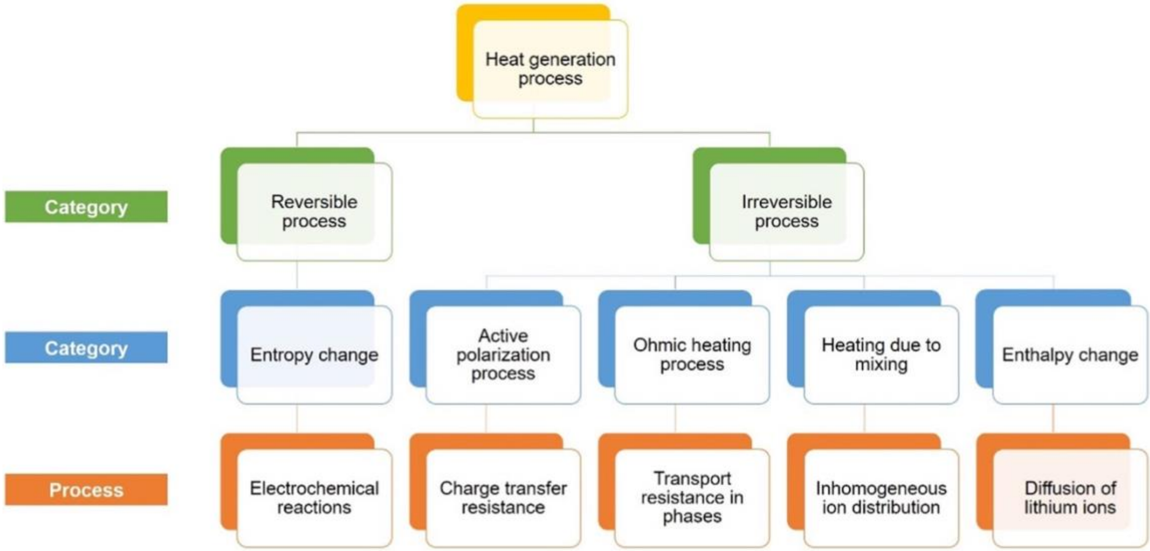


Exhibit 19

Map of all measured trip’s stops (source: https://www.mapcustomizer.com/)

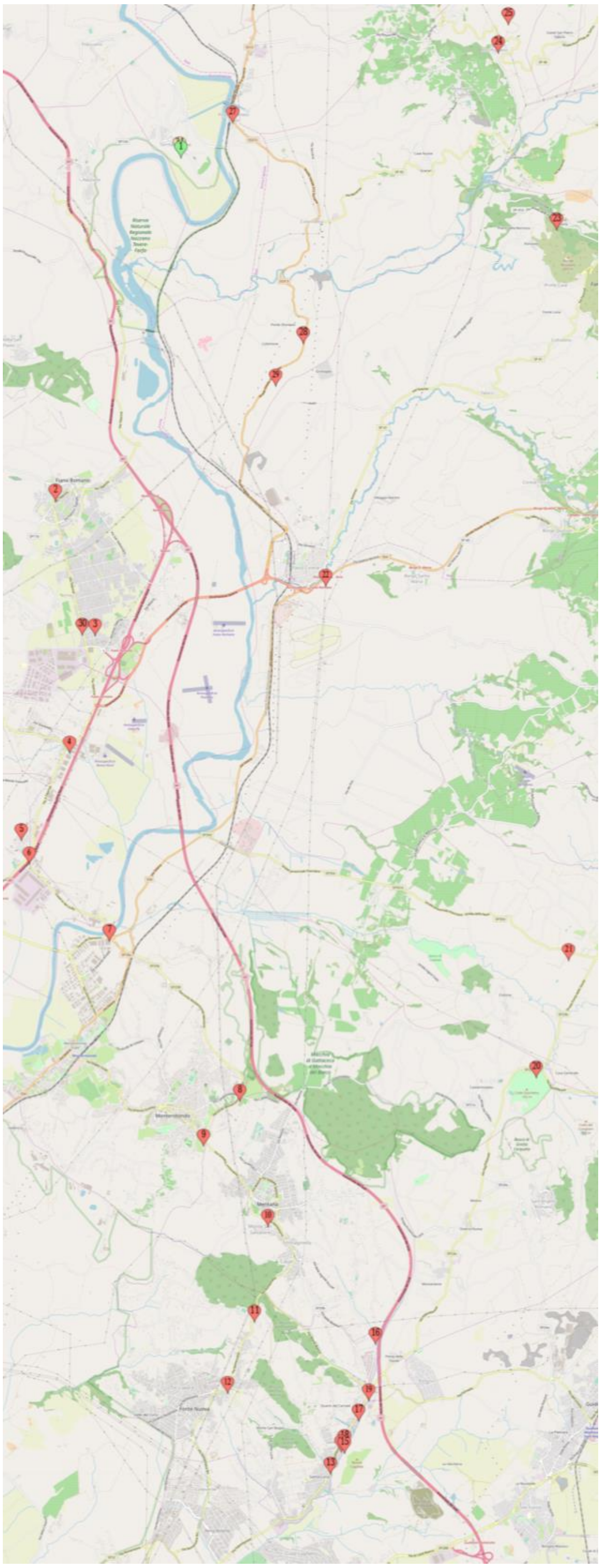


Exhibit 20

Iveco Daily diesel 3.5 tons slope profile (derived from altitude data)

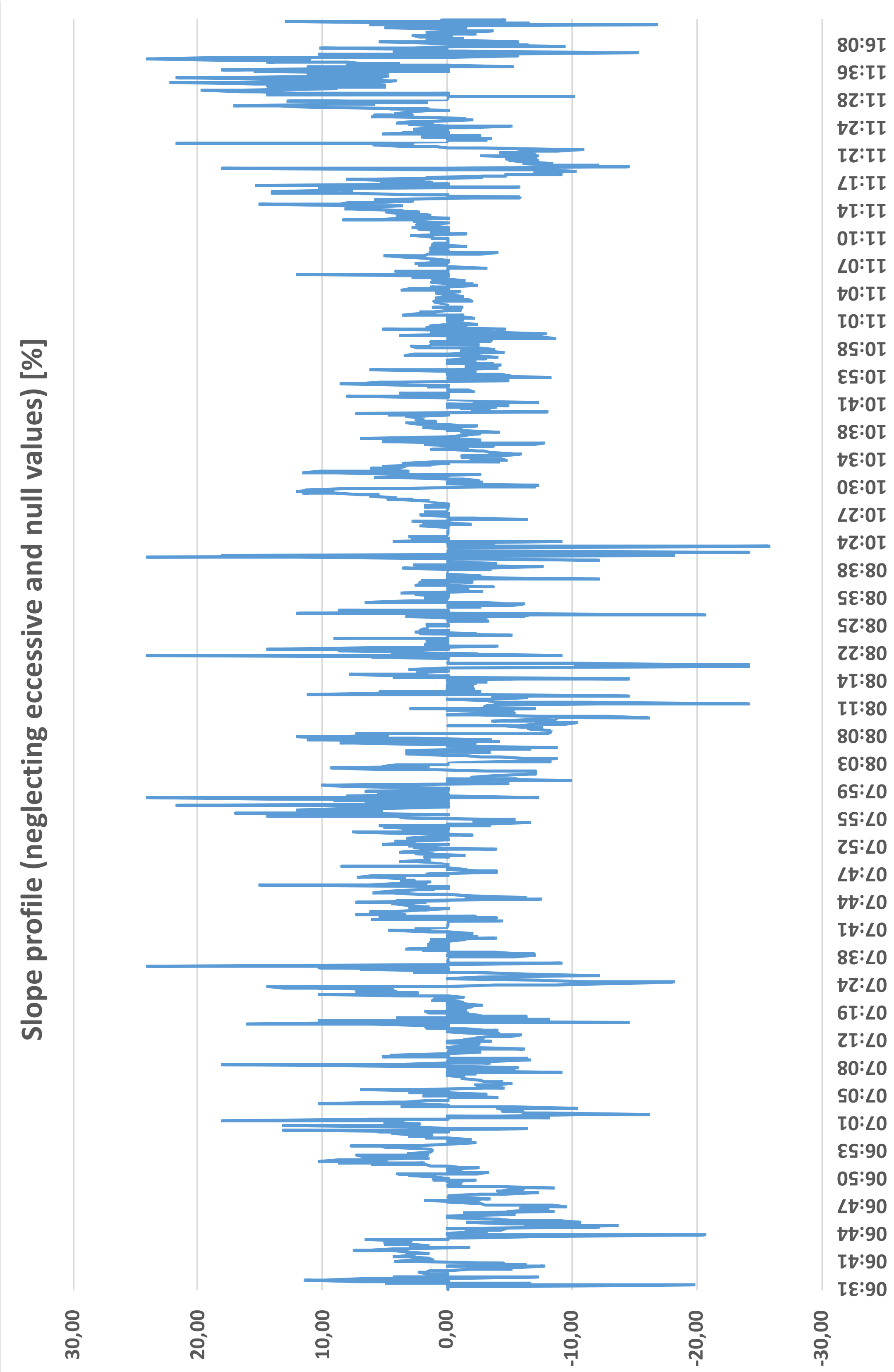
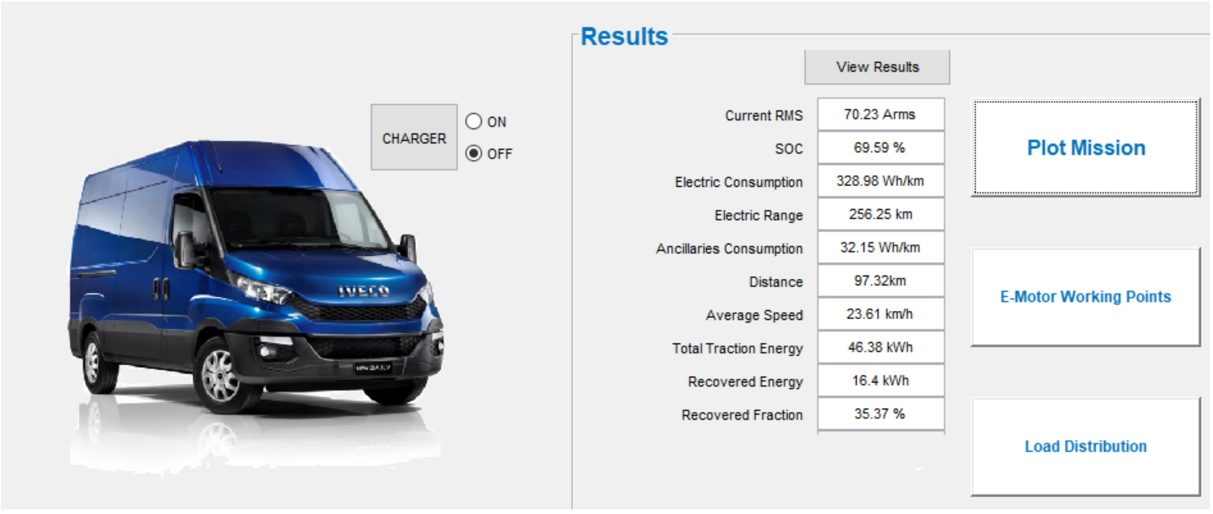


Exhibit 21

Simulation summary output of Path 1 (top) and Path 2 (bottom) for 3.5 tons Daily electric



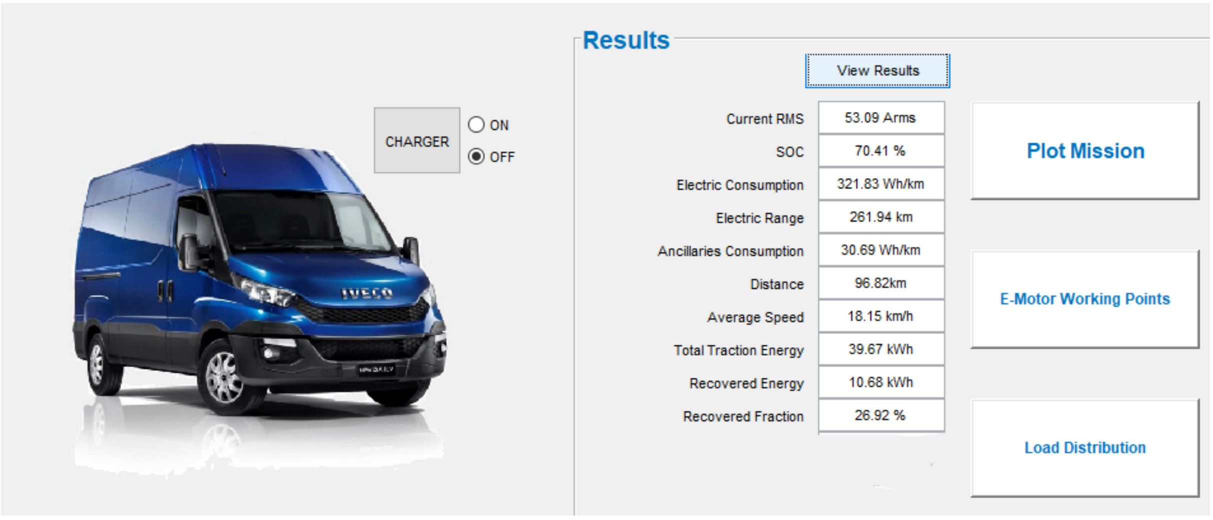


Exhibit 22

Battery current root mean square of Path 1 for the Daily electric 5 tons

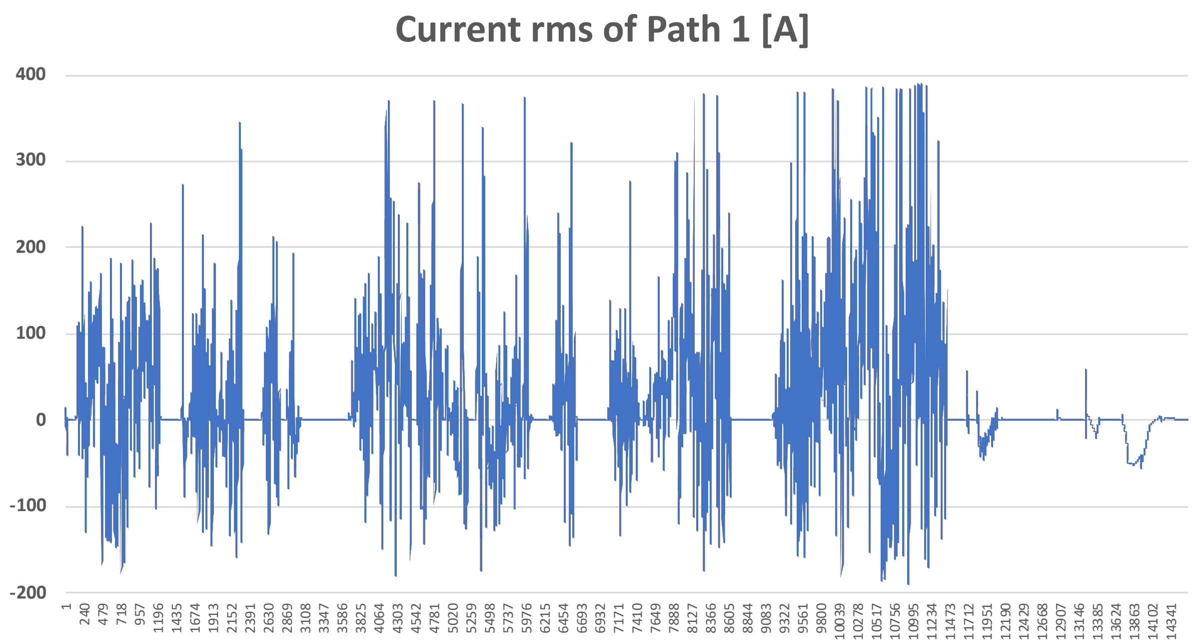
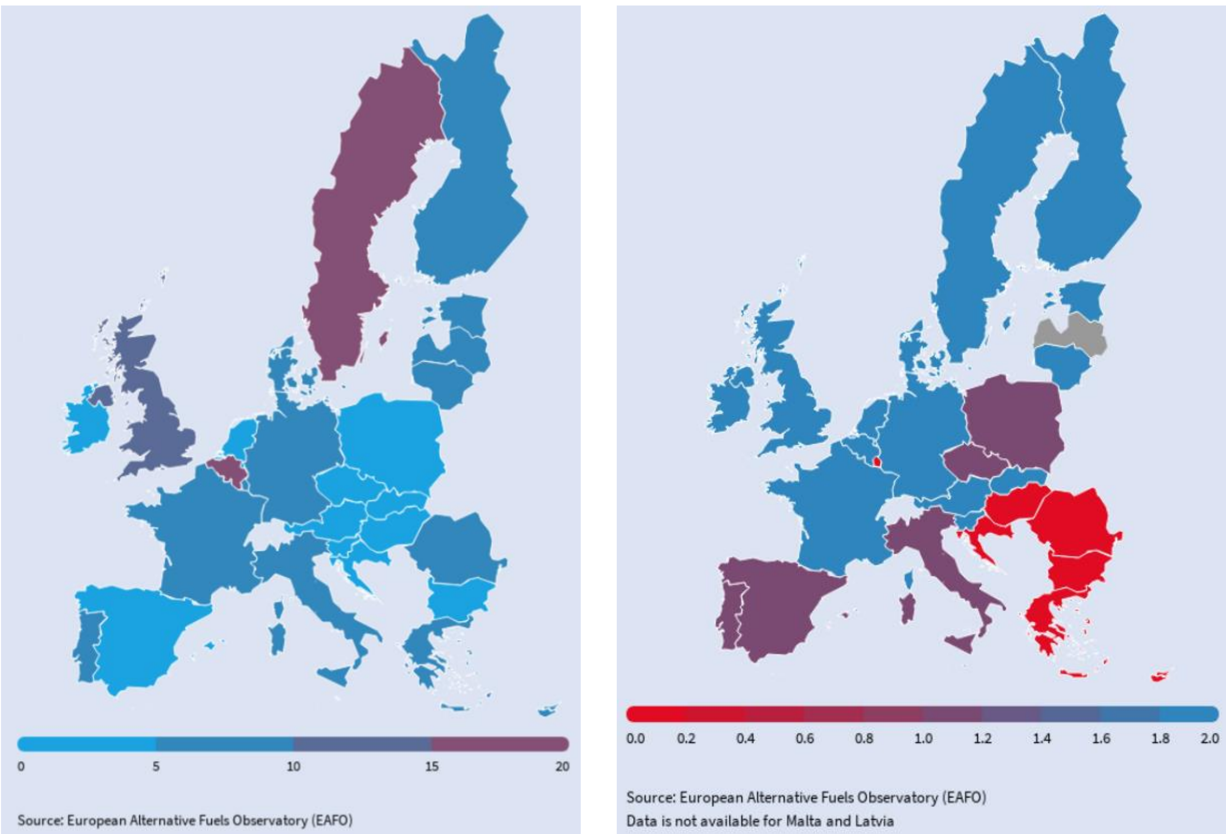


Exhibit 23

Charging infrastructure in Europe (Transport & Environment, 2018). On the left the number of EVs per public slow station, on the right the number of fast stations per 60 km highway



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