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The Impact of Truck Electrification on Urban Logistics

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1. Introduction to the Urban Logistics

1.1 Definition of the Subject

Urban freight transport and logistics operations are concerned with the activities of delivering and collecting goods in town and city centres. These activities are often referred to as ‘city logistics’ as they entail the processes of transportation, handling and storage of goods, the management of inventory, waste and returns as well as home delivery services.

Often many of these processes, or parts of them, are undertaken outside urban areas but they still have impacts on urban operations. Therefore, freight transport and logistics operations in urban areas cannot be viewed and studied in isolation but rather in the context of the entirety of supply chains that typically cross the geographical boundaries of urban areas.

In its current implementations City Logistics includes a subset of the following initiatives, combined and varied for compatibility with transport planning policies for a particular city:

- load factor controls
- underground freight transport systems
- traffic management plans
- advanced travel information systems
- cooperative freight transport systems (including local ‘freight brokers’)
- public logistics terminals (transhipment centres), sometimes termed ‘freight villages’

1.2 Why is Urban Logistics so important?

The urban environment is characterized by high settlement and population densities and high consumption of goods and services.

In Europe, around 75% of the population live in urban areas and this is predicted to increase to about 80% by 2020. Such a population growth combined with shifting consumption patterns – such as a rise in online commerce and flexible deliveries – have led to increasing inner and inter urban (freight) transport.

Furthermore, as urban freight transport deals primarily with the distribution of goods at the end of the supply chain, many deliveries tend to be made in small loads and in frequent trips, thus resulting in many vehicle kilometres. It is estimated that goods transport in cities represents from 10 to 18% of road traffic (COST321, 1998).

In such environments traffic infrastructure and the possibilities for its extension are both limited and unsustainable. This dichotomy between demand and limitations of the urban environment has resulted in significant problems associated with urban freight transport. The most commonly mentioned are congestion, pollution, safety, noise and carbon creation. In fact, the transportation of goods accounts for 40% of air pollution and noise emissions (COST321, 1998). The combined effects of these problems are both economic and societal: they not only reduce the efficiency and effectiveness of urban freight transport and logistics operations but also impact on the well-being of a nation by decreasing the quality of life of citizens and through detrimental effects on health.

Transport currently accounts for half of global oil consumption and nearly 20% of world energy usage, of which 40% is utilized in urban transport. Global transport emissions have risen annually by nearly two billion tonnes of

CO2 equivalent since 2000, with freight transport generating between 20% and 60% of local transport-based pollution (International Energy Agency, World Energy Outlook 2013).

Globally, road transport is responsible for about 16% of man-made CO2 emissions. It is a common misconception that global warming is mainly caused by cars and trucks. It is important to understand that there are other, larger, contributors and ALL sources of CO2 emission must be addressed if the problem is to be solved.

1.3 Challenges

Nowadays, cities and urban areas have to face many challenges – economic, social, health and environmental.

An interesting paper from the ENCLOSE project [1] states: "Customers not only want their goods delivered on time, but precisely when they want them and where they need them. Hardly anyone in a very competitive urban freight market gives any thought to the transport-related implications of increasingly flexible delivery schemes. Consequently, urban freight transport is on the rise."
In Eastern Europe in particular, vehicle kilometres sharply increased over the past 10 years; freight activity in Lithuania and Hungary increased by approximately 50% overall, while annual road-freight transport jumped 75% (Eurostat 2012, online).

The range of activities and sector coverebed by urban logistic operations is rather high, as shown in Figure 1.

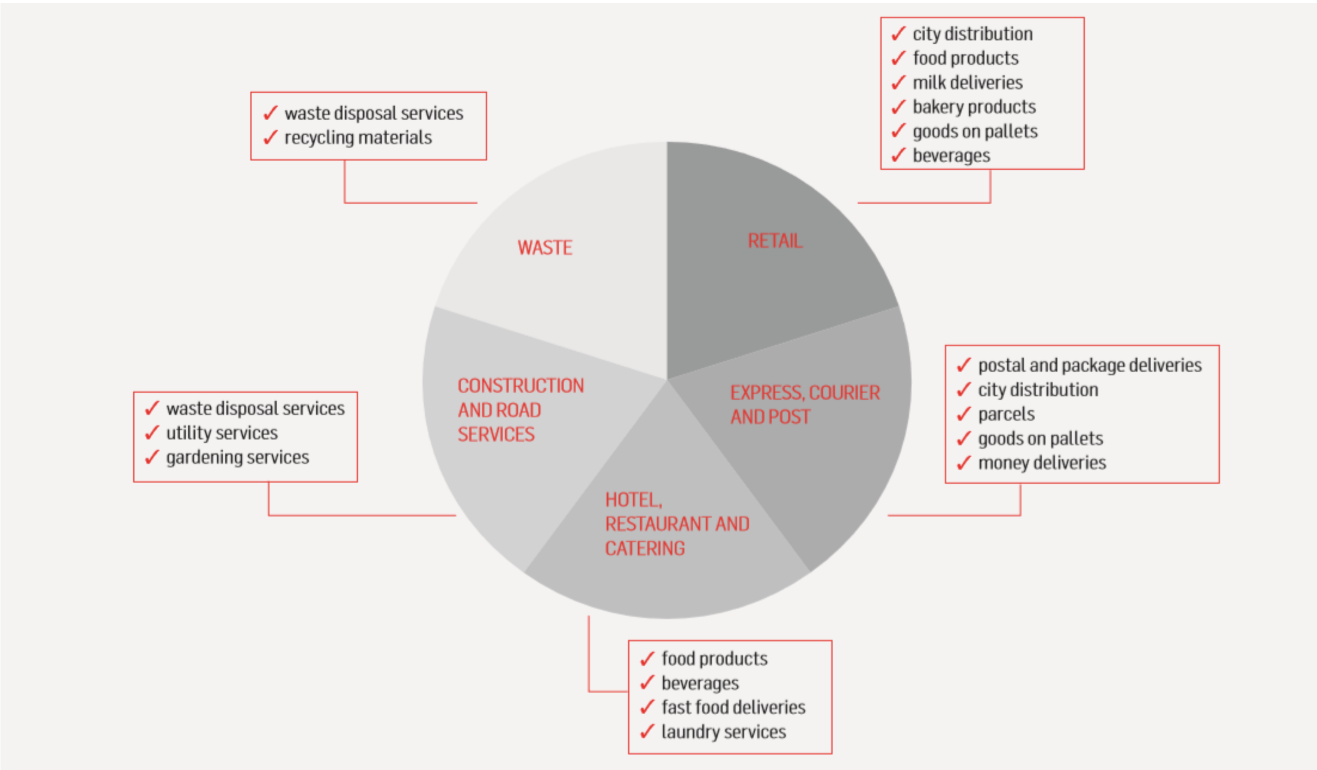


Figure 1: Sectors of Urban Logistics. Source: ENCLOSE project, 2014.

In this work, three sectors have been picked and investigated: Express, Courier and Post (Multi-Drop Delivery), Retail (Local Distribution) and Waste (Garbage Collection).

The express, courier and post sector employs large vans or small to medium sized trucks. Its logistic model is based on consolidated delivery and collection tours departing from cross dock terminals. The number of daily deliveries ranges from 20 deliveries (traditional parcel delivery) to around 90 deliveries (express courier delivery). Consequently, the stop frequency (stops/h) turnsa out to be rather high.

The retail sector, that alone constitutes almost 40% of daily deliveries in cities, is highly fragmented with respect to the demand and supply of freight transport. The consequence is a high number of vehicle movements with low payloads. Studies forecast even further declines in efficiency in future, due to anticipated trends in city centre redevelopment and increasing interest in smaller store formats. In this work it has been analysed under the assumption of the possibility to employ an Urban Consolidation Centre (UCC).

Municipal waste management features the collection and removal of household waste. The sustainability of this sector can be improved by optimizing fleet management and routing (connected vehicles), by minimizing environmental impacts (Hybrid or EVs) and by improving access to waste disposal facilities.

Urban freight logistics and the possibility of delivering and receiving goods and services whenever they are needed are important factors in various market sectors. Urban freight transport also causes economic, environmental and social problems that need to be addressed by offering alternative ways of transporting freight, as shown in Figure 2.

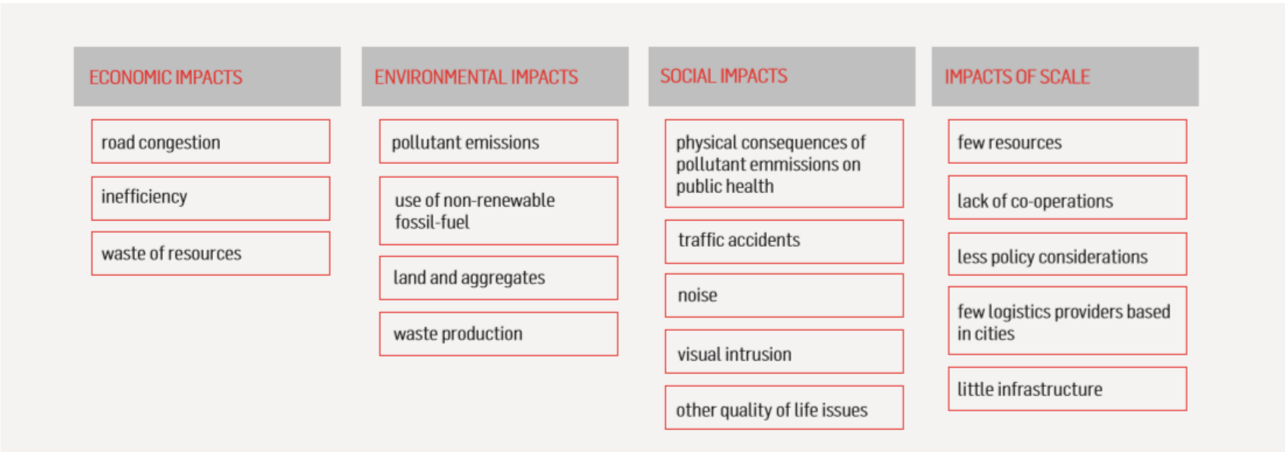


Figure 2: Impacts of Urban Logistics. Source: ENCLOSE project, 2014.

To resume, developments in these sectors have economic, environmental and social impacts. Cities are affected by more traffic, more congestion, more noise and more pollution. The causes of these problems are several: from inadequacy of road infrastructure to inefficiency of logistics processes, resulting from a low load factor to a high amount of individual deliveries.

Small and medium-sized cities are the environments most affected by these negative impacts. Narrow roads and a lack of loading and unloading areas within city centres contribute to produce negative effects that are attributable to the small scale of these cities as well as more pollution and noise. The smaller number of main roads usually leads to higher traffic levels and congestion. The space in small and medium-sized cities is also limited in terms of on-street parking and loading (BESTUFS II 2006, p. 8). Moreover, delivery vehicles in historic city centres are perceived as a visual intrusion: urban heritage areas in particular must meet a number of obligations to maintain their status.

“It is clear that cities need to reduce pollution-intensive freight traffic by managing logistics processes more efficiently and switching to greener vehicles. An “Avoid, shift and improve” approach such as suggested by the International Energy Agency addresses this challenge by suggesting different policy options relating to specific objectives. Reducing trip lengths and the need for travel can help prevent freight traffic. This can be achieved by introducing subsidies or tax incentives for low-carbon transport or by implementing parking standards. Moving freight transport from road to rail and water or shifting to more efficient vehicle models can further alleviate the issues mentioned above. One last step is to improve the efficiency of vehicle and fuel technology and to reduce energy consumption and emissions. The introduction of electric vehicles into logistics fleets is one example for this “improve” strategy, since vehicle fleets and fuel systems can be transformed into zero emission technologies.” [1]

1.4 Dealing with Urban Logistics

1.4.1 Regulatory Measures

As stated by the paper [2] from Civitas, regulatory measures (also called “command and control measures”) are “rules and prohibitions designed to control the activities of private freight operators in order to preserve the liveability of the urban environment and to guarantee an adequate level of mobility.”
They are quite spread thanks to their implementation easiness by city authorities. Also, they usually have a higher degree of acceptability among all stakeholders compared with other kinds of measures. This is due, in the main, to their more traditional nature and apparent equity.

As always, these kinds of regulations must be supported by a control/enforcement system, often electronic, in order to prevent possible infractions.

Among these kinds of measures we can find: Time Access Restrictions, Parking Regulations, Environment Restriction, Size/Load Access Restrictions and Freight Traffic Flow Management.
It follows an analysis, carried out in paper [2], of each of these measures.

1.4.1.1 Time Access Restriction

These measures set restrictions about the times when freight activity can take place. The objective is to reduce freight traffic during peak hours in urban areas and/or to ban night deliveries due to noise issues.
The promotion of off-peak deliveries in cities is a promising strategy for offsetting the traffic impacts of urban freight. Off-hour deliveries have the potential to reduce peak-hour congestion allowing delivery drivers to have a wider time window and to avoid traffic delays. Relaxation of such delivery windows can reduce congestion by helping to spread peak freight traffic.
The main time access restrictions employed are: daytime delivery restrictions, daytime delivery bans, and nighttime delivery bans and silent deliveries.

Strengths

- Improve deliveries reliability
- Improve parking availability during ban interval

- Increase efficiency (load factors)
- Enhance environmental sustainability & safety

Weaknesses

- Require a high degree of coordination among jurisdictions
- Increase congestion during daytime
- Increase operational costs
- Reduce operational capacity

1.4.1.2 Parking Regulations

Unfortunately, the number of parking spaces available for delivery operators is not enough to satisfy the needs of delivery trucks. Carriers are then forced to double-park as the demand for parking exceeds the linear capacity of the streets. A common local policy to organise last-mile delivery operations is the provision of loading/unloading spaces: in fact, lack of delivery spaces leads to congestion and potentially hazardous situations for other street users.

Additionally, the design and location of loading/unloading areas in many cities are often inadequate. Many bays are unable to accommodate trucks (with their handling equipment) and sometimes bays are designed according to a fragmented vision, often in response to the demand of a local shopkeeper, without large scale planning.

Recently, special measures have been implemented: it is the case of 'Peak-hour clearways', streets with parking or stopping restrictions during peak hours. These kinds of measures allow to make the movement of all vehicles easier by increasing road capacity.

The main types of parking regulation measures are: loading and parking restrictions, vehicle parking reservation systems, timeshare of parking spaces, peak-hour clearways.

Strengths

- Reduce traffic congestion,
- Increase efficiency
- Enhance safety and liveability

Weaknesses

- Require enforcement
- Require public and private-sector acceptance and coordination with other parties
- May require additional parking space due to high freight transport demand

1.4.1.3 Environmental Restrictions

The objective of such measures is to reduce the negative externalities produced by freight vehicles, both in terms of emissions and noise, preserving the liveability of city centres . These strategies has a main positive effects: they reduce the environmental impact of freight traffic, fostering the use of clean technologies by promoting the use of electric or low-emission vehicles for urban deliveries. Also, vehicles renewal programmes can be designed to support this type of initiative.

The introduction of Low Emission Zones can either ban all the vehicular traffic, or just vehicles that do not meet

a minimum environmental standard (engine-related restrictions) .
The main environmental restriction measures are: emission standard & engine-related restrictions, noise programmes/regulations, low emission zones.

Strengths

- Enhance environmental sustainability and liveability
- Increase efficiency
- Facilitate off-hour deliveries
- Social acceptability

Weaknesses

- Require high capital investments for the private/ public sector
- Require coordination among municipalities and control/enforcement
- Require cooperation of the private-sector

1.4.1.4 Size and Load Access Restrictions

These kinds of measures are designed to increase the liveability of urban areas by optimizing the use of public space, specifically of public streets. They prevent vehicles of a certain weight or size from using a particular road or area: this may produce benefits on congestion levels and on road accident rates caused by large trucks. Furthermore, in order to reduce the number of freight trips entering a target area, these restrictions can also impose a minimum load factor per truck.
Load factor restriction measures are, however, not easy to implement. Load factors are, in fact, the result of specific market conditions, rather than purely logistical decisions. Moreover, target areas are most often at the end of the delivery chain where the load factor is, consequently, expected to be low.
The main size/load access restriction measures are: vehicle size and weight restrictions, load factor restrictions.

Strengths

- Enhance environmental sustainability, liveability, improve accessibility and safety
- Reduce infrastructure damage
- Increase efficiency and cargo consolidation

Weaknesses

- Very hard to enforce
- Require coordination among municipalities

1.4.1.5 Freight-traffic Flow Management

The objective of these measures is to prevent freight vehicles from using sensitive routes that can be inappropriate in medium-sized urban contexts. These rules impose special restrictions by specifying the routes of the transportation network that cannot be used by freight traffic operators.
Further options are the optimization of available road capacity by allocating rights of way to restricted lanes to

trucks or other categories of vehicles. Lane usage can be allocated to different users according to time windows: it can be shared by all users at specific time periods or assigned only to certain users all day.
The main freight-traffic flow management measures are: truck routes and restricted multi-use lanes.

Strengths

- Discourage unnecessary truck movement in sensitive areas
- Enhance environmental sustainability and safety
- Provide useful info and guidance to cargo drivers
- Increase efficiency

Weaknesses

- Challenging to ensure accessibility
- Require proper communication, education and enforcement by authorities
- Require high degree of coordination among jurisdictions
- May not be adequate for sensitive locations

1.4.2 Potential Solutions

McKinsey, the giant of consultancy, recently published a study [3] on urban logistics and its challenges. After a detailed analysis, it also presented 20 solutions that might improve urban logistics. They are resumed below, sorted by their position in the value chain.

Suppliers

- Order grouping. Group parcels for the same recipient ordered at different times but targeted to arrive around the same time.
- Return management. Develop ways to reduce the number of purchase returns, thus reducing trips.
- On-demand 3-D printing. Reduce average delivery distance by printing items on demand and near the location of the order.

Warehouse and sorting facilities

- Urban consolidation centers (UCCs). UCCs are cross-docking transshipment centers where items are consolidated for delivery into urban areas.
- Warehouse logistics. Optimizing, automating, and integrating the flow of materials and information within a fulfilment or distribution center increases the speed of loading and improves truck utilization.

Transportation

- Electric vehicles (EVs). EVs are quieter and cleaner than traditional cars, particularly when charged using renewable-energy sources.

- Load pooling. The online matching of demand for capacity with available supply maximizes vehicle load utilization; fewer trucks therefore make a greater number of deliveries.
- Route optimization. Finding the best way to get from point to point, including constant updates, reduces the mileage and time drivers need to deliver goods.
- Combining passenger and parcel delivery. Using passenger vehicles as part of the parcel fleet optimizes road capacity.
- Night delivery. Shifting delivery to evening hours, when bigger trucks can be used and traffic is less, can smooth out congestion and reduce the number of trips.
- Bike delivery. Bikes are a clean and agile alternative to vans and trucks for low-weight, low-volume deliveries. E-bikes can deliver larger loads over longer distances.
- Autonomous light commercial vehicles (LCVs) require minimal to no user interactions for driving; this allows the person on-board to focus on the delivery, minimizing stopping time.
- Autonomous ground vehicle (AGV) lockers. These are parcel lockers on wheels that customers open using a personal code.
- Drones. Unmanned aerial vehicles could deliver individual packages, using no roads.
- Droids. These small four-wheel cars go autonomously from one point to another on city sidewalks, carrying goods for delivery. Unlike drones, which need landing space, droids could be deployed in denser cities.

Point of delivery

- Parcel lockers. These are sited in a place where customers can pick up packages at any time with an access code sent to their mobile device.
- Individual parcel boxes. These are similar to individual household letter boxes but are large enough to fit parcels and sometimes temperature regulated. The result is fewer failed deliveries.
- Click and collect. Buying online and picking up at the store reduces the number of failed deliveries and can help to reduce congestion, as many consumers will avoid peak hours.
- Trunk delivery. Use the trunks of parked vehicles, opened with a special key or code, as mobile addresses for package deliveries. Because recipients do not have to be available to accept a parcel, failed deliveries are reduced.
- Dynamic hand delivery. Tracking a recipient’s location and delivering parcels directly to where the consumer is at that moment minimizes failed delivery attempts.

From the same paper of McKinsey, the results of the assessment are reported in Figure 3. They are evaluated in terms of Cost Effectiveness, Customer Preference, Environmental Impact, Technological Maturity and Infrastructure.

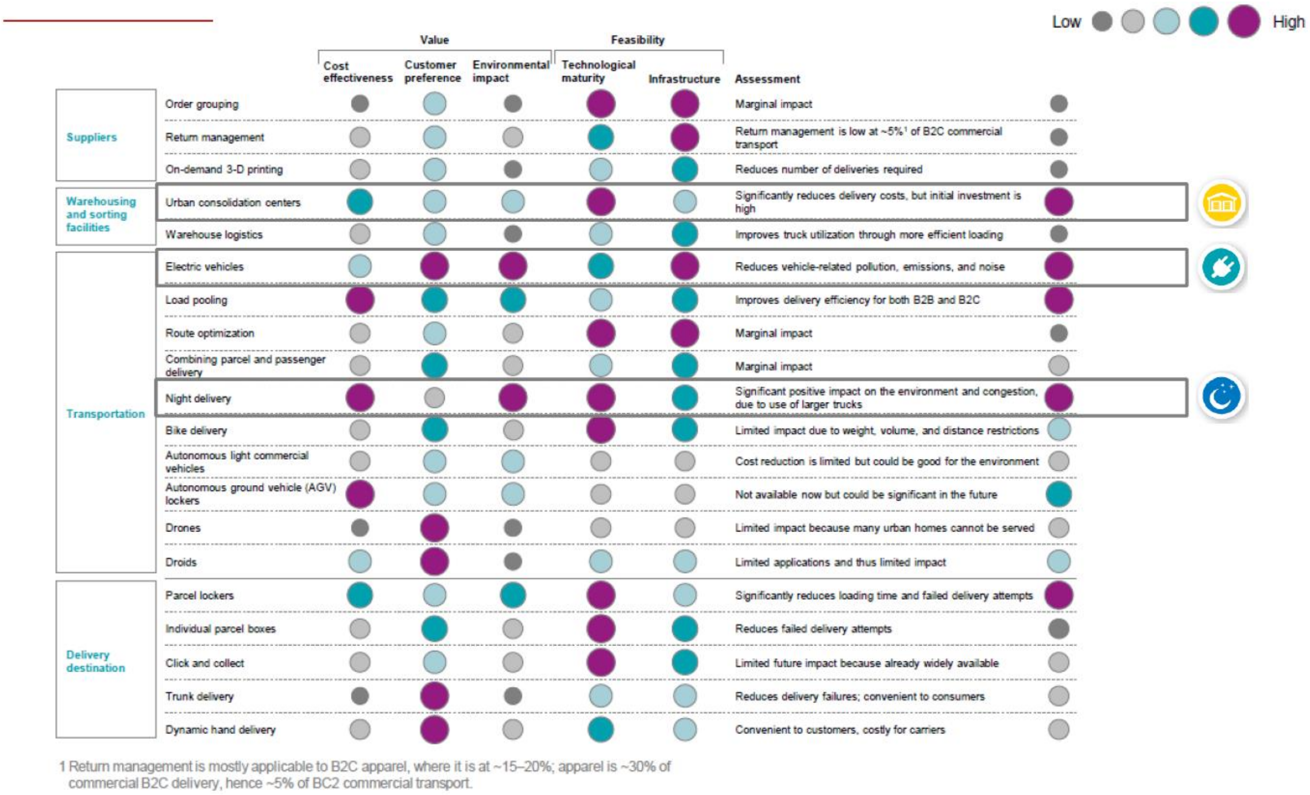


Figure 3: Assessment Results. Source: McKinsey

The results are clear: all the mentioned solutions appeared promising. Anyway, three solutions stand out from the list. In the following sections, they are analysed in detail.

1.4.2.1 Urban Consolidation Centers

The idea of UCCs is not new. Some have failed due to high costs and less-than-expected demand, some were located too far from the city center and others were too noisy or did not have effective tracking systems. All these lessons are being incorporated into the next generation of UCCs.

Moreover, UCCs are being favoured by a number of trends: rising demand for e-commerce, technological advances, and public concerns about traffic and pollution. São Paulo, for example, is trying to limit the number of trucks entering the city, while London, Singapore, and Stockholm have imposed congestion charges. UCCs work well with these and other efforts, because they encourage the use of higher load factors and of vehicles that take more efficient routes, which means fewer trucks entering congested areas.

The impact of a UCC on the logistic model is shown in Figure 4.

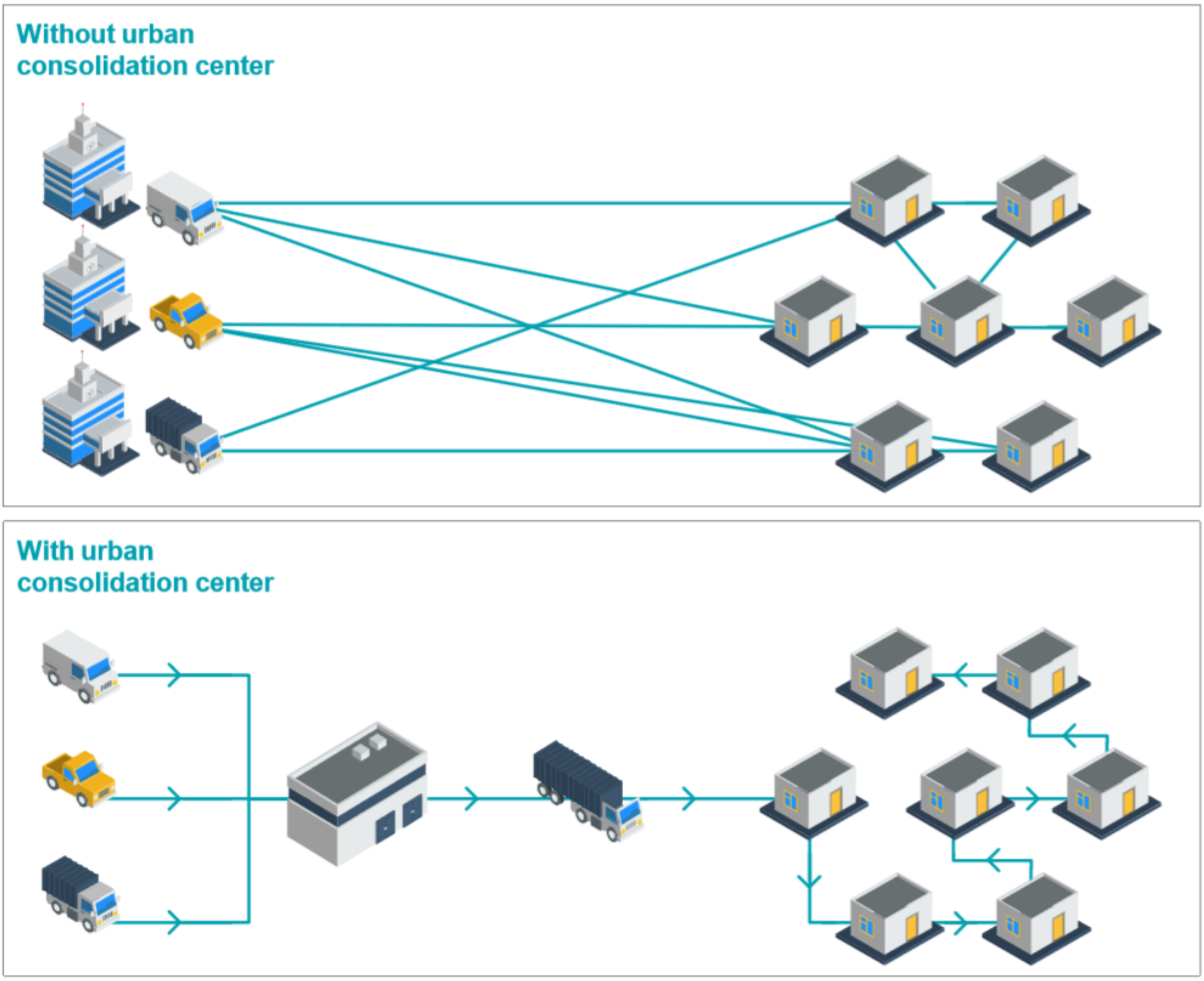


Figure 4: Impact of UCC on the Logistic Model. Source: McKinsey

UCCs give companies a location, typically just outside the city center, to which suppliers and retailers can ship their orders. With the goods being gathered in one place, they can be consolidated into fewer deliveries. Most of trucks entering a city are nowadays underutilized, exhibiting low load factor and then room for more cargo. The use of UCCs enhances maximum load factors, thereby reducing the number of vehicles that enter the city. Experience has shown that UCCs work best in dense cities, not being more than 30 kilometers far from the city center, and being close to highways.

McKinsey estimates that companies in developed, dense cities that deploy UCCs could save 25 percent on delivery costs per parcel (compared to traditional methods), due to greater capacity utilization, lower labor costs, and fewer miles driven. Also, the mileage could be reduced by as much as 45 percent to deliver the same volume of goods, thus reducing general wear and all types of vehicle emissions (Figure 5). It is worth to notice that the benefits in sprawling cities will not be as large due to the greater distances between delivery spots.

Even if technological barriers are minimal, the main obstacle to the diffusion of UCCs is the high capital cost required. Still, the investments can be worth it. UCCs that have worked well are often in cities that forcefully promote them, either through direct intervention or indirect standards that help develop the necessary economies of scale.

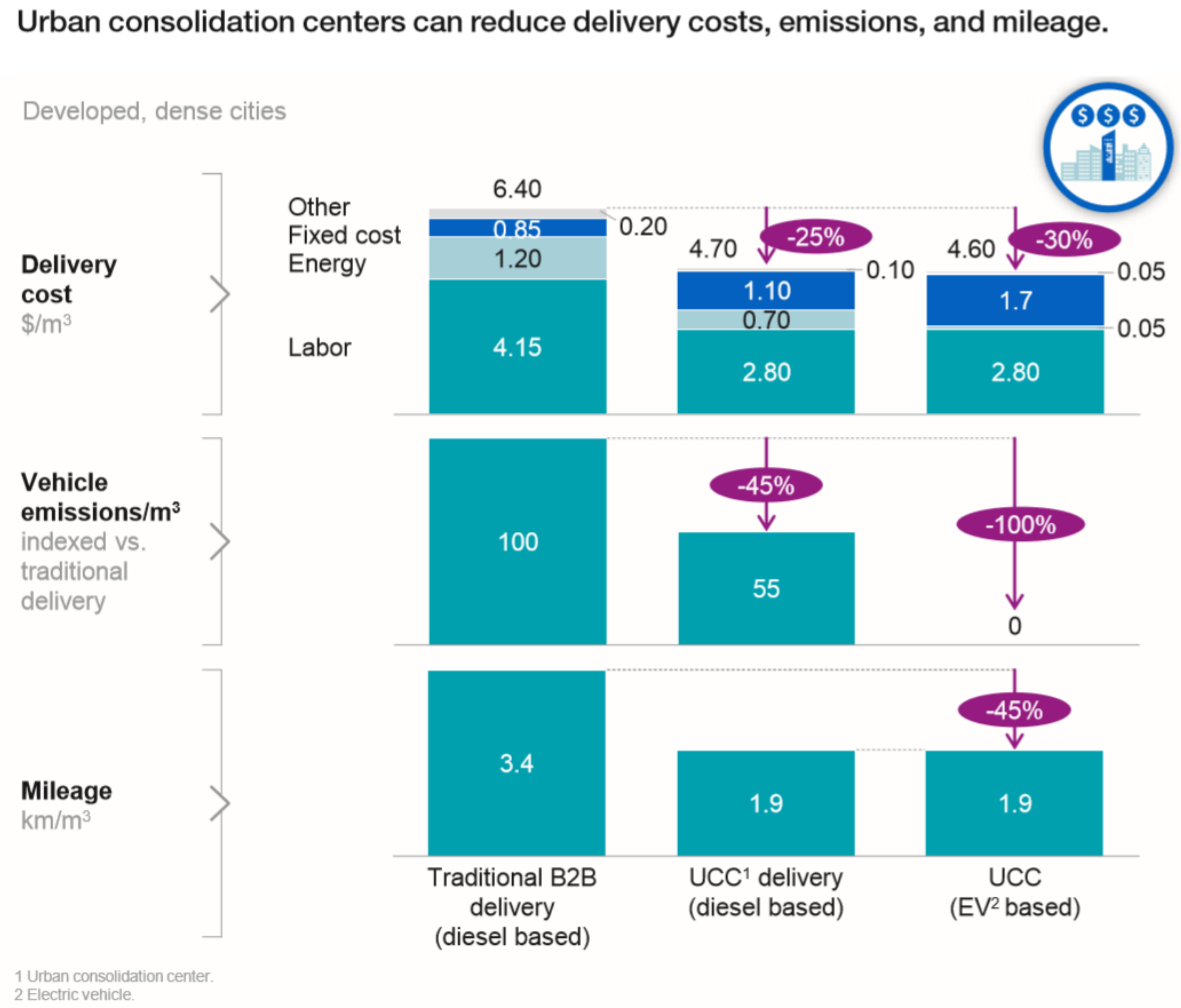


Figure 5: Benefits of UCCs. Source: McKinsey

1.4.2.2 Night Delivery

Night delivery may bring major benefits. Nowadays, the practice is limited, primarily due to residential noise concerns. Such concerns may be easily overcome through the use of EVs. Other issues include the higher pay needed for late-shift workers and the willingness of consumers, whether individuals or businesses, to receive packages in the off-hours. Still, these issues may be easily overcome combining night deliveries with the use of parcel lockers.

McKinsey estimates that at its full potential and in a developed, dense city, night delivery could save up to 40 percent in total delivery costs, while also cutting vehicle emissions, due to fewer miles traveled (Figure 6). Not only is night delivery feasible right now: further developments, such as the use of autonomous vehicles, could make it even more economical.

There have already been night-delivery initiatives. In 2003, the administration of Barcelona kicked-off an experimental program in 20 locations to allow commercial deliveries from 11:00 PM to 6:00 AM. , The results were very promising: two larger night trucks could carry as much as seven day trucks. In that occasion, to mitigate noise problems during driving and unloading, delivery vehicles were fitted with noise-canceling devices. Today, the same results can be obtained with EVs.
The program worked so well that it was subsequently spreaded out to more than 140 cities across Spain. Moreover, one supermarket chain estimated that it would take less than three years to see a return on the investment, in large part because trucks could go three times as fast at night as during the day.

Figure 6: Benefits of Night Delivery. Source: McKinsey

1.4.2.3 Electric Vehicles

All the automotive companies are increasing investment in EVs; meanwhile, battery prices are falling, and vehicle-emissions standards are tightening. Inevitably, then, EVs market share is going to grow. The question is not anymore whether electrification is going to happen—it is—but how fast.

So far, most of the discussion has focused on the passenger sector. However, for the urban commercial delivery trucks' route characteristics, infrastructure requirements, utilization, and torque requirements, EVs look to be a promising solution.

- Route characteristics. In densely populated regions, delivery vehicles typically travel predictable and relatively short routes. For these reasons, battery size can be optimized, minimizing cost.
- Infrastructure requirements. Creating a charging network for passenger cars is difficult due to the unpredictability of where and when consumers will need to charge. For short and medium-range commercial vehicles, this is less of a problem. They will usually not need to charge during their delivery routes and can return afterward to a local charging hub.
- Utilization. One of the barriers for passenger-vehicle electrification is that private vehicles are typically parked 90 percent of the time or more. While operating expenses for EVs are dramatically lower than for traditional vehicles, it is difficult to create a return on their higher capital costs with such a low average utilization. Because CVs are used more intensively—typically for at least a full shift—their higher utilization can overcome the capital-expenditure-versus-operating-expense conundrum.
- Torque capabilities. CVs are often equipped with diesel engines because diesel's higher low-end torque performance is superior to that of gasoline engines. Electric motors, however, with their flat torque performance across the full range of motor operation, are even better than diesel engines at low-end torque.

The electrification of the commercial fleet would also provide considerable benefits to city residents.

First, many urban areas are struggling with smog and pollution. There may be debate on the well-to-wheels emissions of EVs versus ICE vehicles, especially in places where EVs are charged with carbon-intensive sources of power, but there is no question that electrification of the commercial fleet would significantly reduce the smog-inducing NOx and particulate matter that large diesel engines emit.

Second, electrified delivery fleets help to reduce noise. EVs are much quieter than diesels, especially during idle times. This could constitute a significant asset in expanding night deliveries, which are discouraged in large part due to noise concerns.

Third, EVs will likely help to improve traffic flow. Conventional trucks accelerate slowly, reducing the average speed of traffic. Electric trucks, with their increased torque, accelerate more quickly.

2. State of the Art of Heavy Good Vehicles in Urban Logistics

2.1 Mission and Requirements

The ease of the delivery and collection of goods in urban areas has a significant influence on the economic power, quality of life, accessibility and attractiveness of the city.

Given the limited space available in urban areas and the quite common access restrictions, HGVs find in the urban environment their toughest challenge.

Due to their mass, these vehicles emit serious quantities of GHG. Heavy-duty vehicles (HDVs) represent only 4% of the on-road fleet in the European Union, but are responsible for 30% of on-road CO2 emissions.

This explains why usually HGVs are not allowed to enter in the urban city centres.

Anyway, it is important to ensure that logistics systems can operate effectively in urban environments. For this reason the technological challenges for HGVs are quite urgent and demanding.

Urban logistics must contend with a variety of challenges, whilst catering to increasingly demanding consumer choices. Many local authorities in Europe impose access restrictions on freight vehicles. They restrict the movement of freight vehicles in city centres according to time, size, or weight. As a result, operators of goods transport are forced to adjust their logistic systems to deliver goods to such areas within the imposed time frame and/or to use smaller vehicles.

Such restrictions differ among different municipalities and are often unclear or inconsistent. These factors cause grave difficulties for operators that have to organize national-wide supply chains while responding to increasingly stringent customer demand for frequent, just-in-time and reliable deliveries.

Freight distribution is an increasingly important part of modern city life.

Most goods consumed in our cities originate externally and the transport elements within the cities are often referred to as the "last mile" in the supply chain. Trucks remain the dominant transport mode as they are perceived to be most suitable to move goods between specific origins and destinations within the complex urban grid of streets.

However, trucks generally have significant environmental impacts such as CO2, NOX, particulates (PM10, PM2.5, PM1), and noise emissions. Traffic safety and parking requirements for delivery vehicles are also of concern. While greenhouse gas emission effects are felt on a global level, others are felt locally. For urban areas the last mile poses the greatest problems for the environment, customers/ citizens and logistics service providers. Therefore, promoting and sustaining alternative and sustainable strategies and solutions suitable to the urban environment is a critical aspect of urban transport planning.
The good news is that something is changing. Mercedes and Tesla have recently announced their first-ever all electric truck proposals.

HGVs currently make up less than 5% of vehicles on the road, but emit 30% of road transport's CO2 emissions.

Therefore there is need to:

- Increase energy efficiency, which can be achieved by improving the efficiency of the whole urban logistics system added to the expected gains in the energy efficiency of vehicles.
- Improve the urban environment by increasing air quality and reducing noise.

- Increase customer satisfaction by delivering the goods on time and improving the reliability of the system.
- Increase safety and security reducing injuries and fatalities and also cargo lost or damage.

2.2 Technical Analysis of Available Powertrains

2.2.1 Conventional Powertrains: Fuel Efficiency Technologies

A first distinction has to be made between the two categories that compose the HGV family: tractor-trailers and rigid trucks. According to a study [4] of the International Council of Clean Transportation, also called ICCT, thermal engines have still some considerable potential to decrease CO2 emissions.

In the following section the future technologies which might decrease rigid trucks HGVs emissions are highlighted, in order to understand the future competitivity of thermal engines compared to electric proposals that will be analysed in the next chapters.

The ICCT research made use of the Autonomie vehicle simulation platform to incorporate advanced technologies into the baseline vehicle models. No structural changes to the architecture of the model or the driver parameters were made. The following sections about engine, driveline, road load, and accessories describe the individual technologies that were applied to the baseline vehicle as well as their impact on fuel consumption.

The portfolio of individual technologies available for the reduction of fuel consumption of rigid trucks is similar to that of tractor-trailers.
Two technological steps are considered in the ICCT analysis: a **mid-term** package that includes currently available technologies expected to be deployed in the fleet in the 2020‑2025 period and a **long-term** package that includes in-development technologies and available technologies requiring a large capital investment (e.g., hybrid powertrain), which are expected to be deployed in the 2025‑2030 period.

2.2.1.1 Engine Technologies

Internal combustion engines with compression ignition were born in 1890. Since then, the diesel engine has gradually evolved into its current form. Given the high engine's technological maturity, the many technologies available and under development to reduce engine fuel consumption have a limited improvement potential when applied individually. However, when applied in the form of packages, the efficiency improvements can be significant.

It is then important to understand the individual technologies and to evaluate their interactions at the system level.

Combustion optimization
The combustion process in diesel engines is a complex phenomenon that is strongly dependent on how the injected fuel is mixed with the limited amount of air contained in the cylinder. As such, the injection strategy has a heavy influence on the combustion efficiency and then on the fuel consumtpion.
Higher pressure results in smaller and faster fuel droplets at the exit of the injection nozzle, which in turn

improves the fuel mixing and evaporation. The use of increasingly higher fuel pressures has been mainly driven by the higher exhaust gas recirculation (EGR) rates needed for nitrogen oxides (NOx) emission control. EGR on one sidereduces the peak combustion temperature and the formation of NOx; on the other side, the higher EGR rate slows down the combustion chemistry and reduces the soot oxidation, resulting in higher fuel consumption and particulate matter (PM) emissions. Higher fuel injection pressures are then necessary to offset these disadvantages of high EGR rates. For the latest Euro VI engines, the fuel injection pressure has risen to a maximum of around 2,700 bar and injection systems able to deliver 3,000 bar are commercially available. For engines with lower EGR rates, the required pressure is below 2,000 bar.

Another important strategy for combustion control features the adjustment of the fuel injection rate throughout the injection event. This can be done through multiple injections or injection rate shaping. In the future, flexible injection systems in heavy-duty applications, such as continuous injection rate shaping or closed-loop combustion control, will provide additional freedom to engine calibrators: this will enhance an optimization of the fuel consumption while keeping the pollutant emissions within the required limits.

The use of higher volumetric compression ratios offers theoretical benefits on the brake thermal efficiency; however, the increased friction and higher heat losses produced by the higher temperature and pressure can offset the efficiency gains by more than half. The current average compression ratio of European HDV engines is around 18 and is expected to increase to 20 in the future.

The combustion chamber geometry and the injector configuration can significantly influence the combustion process and, then, the emission formation and fuel consumption. The optimization of the combustion chamber and injector configuration is nowadays an active area of research. However, the applicability of a given geometry is limited to a specific engine and a one-size-fits-all approach does not exist.

Lastly, the timing, duration, and lift profile of the intake and exhaust valve trains impact the fuel consumption and performances of internal combustion engines. Variable Valve Actuation (VVA) is a mature technology that has been applied extensively in LDV engines. Anyway, in large diesel engines, VVA offers limited benefits due to the narrower speed range, higher air flow requirements, complex EGR and turbocharging technologies, and the smaller clearance volume at top-dead center. Despite that, VVA cannot be ruled out as a future technology for HDV diesel engines, as it provides flexibility for charge motion control, cylinder deactivation, internal EGR, extended expansion ratio, ignition delay control, and thermal management of the exhaust aftertreatment system.

Heat transfer losses and waste heat recovery systems

Heat transfer to the environment is a significant fuel energy loss mechanism in internal combustion engines. In modern HDV diesel engines, heat losses can reach 20% of the fuel energy. They take place in the coolant radiator, Charge Air Cooler (CAC), EGR cooler and directly to the surrounding ambient air. The concept of a Low Heat Rejection Engine (LHRE) was already subject of a body of research during the 1980s; however, the theoretical potential of LHREs did not materialize in the magnitude that the research community expected. Furthermore, the resulting higher temperatures of LHREs caused additional challenges due to the thermal fatigue of the engine components and the deterioration of the properties of the lubricants.

The scientific community agrees that a greater potential exists in Waste Heat Recovery (WHR) than in LHRE concepts. WHR systems can convert the rejected thermal energy from the combustion process back into usable mechanical or electric energy. WHR systems tap into the hot exhaust gases and cooling flows as heat sources and use either thermoelectric generators (TEGs) or a closed Rankine cycle for power generation.

A computational study carried out by Volvo trucks, the University of Liege, and the University of Lyon estimates that an optimized WHR system can provide 4.1% and 7.2% of the engines work under steady and transient conditions, respectively. Also, the *European NoWaste Project* showed that a WHR system based on an ethanol Rankine cycle can provide between 1.5% and 3% of the total engine power at steady-state conditions. A recent study on WHR systems used simulation, test bench, and public road testing to assess the potential of an Organic Rankine Cycle (ORC) applied to a Euro VI, 353 kW, 11-liter engine. The results indicate a potential fuel consumption reduction of up to 3.5% over real-life European operating cycles.

Engine Accessories

The correct functioning of the engine is possible thanks to several supporting systems, also known as engine accessories. These include the low and high-pressure fuel pumps, and the coolant fluid and engine oil pumps. The power necessary to drive these accessory loads is usually taken directly from the engine, through the belt: this means that the power produced by the engine has to be used not only to generate torque to the drive shaft, but also to carry these components. Summed up, they can absorb up to 30 bhp, depending on the load, thus having a considerable impact on the fuel consumption.

Decoupling the accessories from the engine has the potential to reduce fuel consumption by engaging the loads based on the engine operating conditions (on-demand control) and by optimizing the moment when the accessories are engaged (e.g., the vehicle's inertia can be used to drive the loads).

Table 1 shows a summary of the technologies aimed at reducing the engine accessories' power consumption.

System	Fuel-saving technology description	Further information
Fuel system	Electric lift pumps allow fuel metering to the high-pressure fuel pump and enable on-demand control of the low-pressure fuel system.	Sommerer, Schmid, Lengenfelder, & Thomas, 2015
Coolant and oil pumps	Active control of the cooling and oil pumps can be achieved through viscous-couplings or through complete pump electrification. The first approach is available due to the progress in visco-clutch fans, while the latter requires a higher voltage architecture.	Boëté, 2015; Schultheiss, Edwards, Banzhaf, & Mersch, 2012

Table 1: Fuel-saving technologies for engine accessories. Source: ICCT study.

Engine friction reduction

Depending on the speed/torque operating point, engine friction can produce losses of up to 4.5% of the fuel's energy. The engine friction losses are originated by piston assembly (45%), hydrodynamic lubrication of bearing and seals (30%) and valve train and other engine components (25%). Given the importance of the piston assembly on engine friction, significant research efforts have been made to understand the friction mechanisms of the piston ring pack, the piston skirt and the lubricant properties.

Significant improvements can be obtained by:

- optimizing the piston rings' shape, tension, and material;
- improving the piston skirt surface geometry and finish;
- reformulate the lubricant for a reduced viscosity.

As mentioned in [4], this potential was also demonstrated experimentally in a project called "CO_2RE", conducted by a group of several European stakeholders. Using a 7.7-liter engine as platform (Daimler's OM 936) and focusing on the piston assembly and oil viscosity, the CO_2RE consortium was able to reduce the piston-related friction up to 36%, translating to a fuel consumption reduction of over 1%.

Similarly, the U.S. Department of Energy is currently funding research efforts to reduce the frictional losses of modern engines by 50%.

Aftertreatment system improvement

The continuous tightening of HDV emission limits in Europe pushed manufacturers to develop and implement several technologies. A current Euro VI compliant emissions control system typically features an EGR loop, a diesel oxidation catalyst (DOC), a selective catalytic reduction (SCR) system, and a diesel particulate filter (DPF). It is worth to notice that the physicochemical principles dictating the formation of NOx and PM in the combustion process give rise to a well known NOx/PM trade-off. It follows that the specification of the emissions control system heavily impacts the engine calibration strategy and, consequently, the engine efficiency. The following two approaches illustrate this interdependence.

- *High engine-out PM emissions:* delayed injection timing and higher rates of EGR reduce the combustion temperature and result in low NOx formation. Anyway, in this way the soot oxidation rates are reduced, thus resulting in higher engineout PM emissions. The DPF system and its regeneration strategy are tailored to accommodate the higher PM flow, while at the same time relaxing the NOx conversion efficiency requirements of the SCR system. The delayed combustion phasing and the backpressure from the EGR and DPF systems negatively impact the fuel efficiency.

- *High engine-out NOx emissions:* lower EGR rates and injection timings optimized for higher fuel efficiency can cut engine-out PM emissions. Anyway, the increase in combustion temperature results in higher engine-out NOx emissions. The SCR system and the urea injection strategy need to be optimized to deal with the higher NOx flow, while relaxing the requirements on the DPF and its regeneration. The earlier injection and combustion timing, together with the lower backpressure from the reduced EGR rates and DPF loading, result in better fuel efficiency.

Improvements in the efficiency of SCR systems have the potential to allow the emissions control strategies to migrate from the first approach (more commonly found in Euro VI HDV) to the second approach. A key and active area of research on SCR systems is the improvement of low temperature NOx conversion, for exhaust temperatures below 300°C. Higher conversion efficiencies can be achieved through modifications on the catalyst substrates, the urea solution, or the control strategies.
Developments are also occurring in DPF substrates aimed at reducing the back pressure from the soot and ash loading in the filter.
A final technology pathway is the integration of SCR and DPF systems into a single substrate in other to improve the catalyst warm-up, improve packaging, and reduce the aftertreatment system backpressure.
Combined, aftertreatment improvements have the potential to reduce fuel consumption by 2% to 4% in line-haul applications [5].

Turbo systems
The use of turbines for the extraction of unused exhaust energy is a concept as old as the combustion engine itself. Two approaches can be distinguished: turbocharging and turbocompounding.
Turbocharging technologies have matured significantly, expanding their operation ranges and thermodynamic efficiency, and have become a standard technology in diesel engines, ensuring high levels of efficiency and powerdensity. Nevertheless, turbocharging technology, and its integration with the engine and aftertreatment system, is still relevant for improving the fuel consumption.
Several turbocharging configurations are available to satisfy the needs of different powertrain concepts. These include single-stage waste-gate turbocharger (WGT), single-stage variable geometry turbocharger (VGT), single stage asymmetric twin-scroll turbine (ATS), two-stage fixed geometry turbocharger (WGT+FGT) and two-stage variable geometry turbocharger (VGT+FGT) [6]. The selection of the turbocharging architecture and the matching of the turbine and compressor wheels is a complex process that heavily influences the powertrain efficiency. Several factors are considered in this matching process, such as cost, low speed torque, high speed power, transient response, desired boosting level, and required EGR rate.

Improvements in the turbine and compression efficiency, as well as the reduction of the backpressure generated by the turbocharger, can result in fuel efficiency improvements of up to 5% [5].
Another way to extract work from the exhaust energy is turbocompounding. In this case the work extracted by the exhaust turbine is not used to compress intake air, but to perform tractive work. In mechanical turbocompounding systems, the recovered energy is transmitted directly to the crankshaft. The mechanical coupling results in a fixed ratio between the turbine and the engine speeds. This reduces the flexibility of the system and can result in additional power losses at low exhaust flows typical of low engine speed operation. Electric turbocompounding uses the extracted energy to power an electric generator and stores the produced electric energy in a battery. As such, electrical turbocompounding provides greater flexibility regarding energy management as the recovered electric energy can be used to power electrical accessories, provide direct assist to the powertrain, or improve the boosting transient response through an electric compressor. In the case of long-haul HDVs, turbocompounding can result in fuel consumption reduction between 3% and 4.5% [7].

Engine technology packages
The effectiveness of individual technologies is hard to isolate because of the deep interaction among the different engine systems. Due to this difficulty, engine technology packages, developed for a previous ICCT study that focused on the North American market, have been used in the ICCT study.
These packages are still applicable because they started from a baseline U.S. EPA 2010 compliant engine, which is very similar in terms of hardware, efficiency levels, and emissions controls to a Euro VI engine. Table 2 summarizes the engine technology packages considered in the ICCT study.
Starting from the baseline Euro VI engine, the next step represents an incremental technology deployment to achieve current best-in-class engine efficiency (2017 BIC). The 2020+ package utilizes well understood, commercially available technologies that allow the engine to obtain 49% peak brake thermal efficiency. This technology level is expected to be achieved by 2020 and commercialized by 2025 at the latest. The advanced 2020+ with WHR package adds a WHR system that increases the peak BTE to 51%. WHR systems are expected to be commercialized by 2027 at the latest.
Finally, the long-term engine package represents technologies that are being analysed in manufacturer research and development laboratories, government agencies, and universities. These technologies would enable peak engine BTEs of 55%, which is an objective of the U.S. Department of Energy (NAS, 2015). Although current prototypes with these efficiency levels do not yet exist, Cummins, a major American mechanical manufacturer, demonstrated during the U.S. SuperTruck program a diesel engine with a peak BTE of 50%, and laid out the pathway to achieve 55% peak BTE through the use of advanced combustion, turbocharger efficiency improvements, and waste heat recover. Similarly, in Europe Volvo and researchers at Lund University are setting a pathway for 56% peak BTE through the use of split cycle engines, where the compression and expansion processes are split into a low-pressure and a high-pressure cycle.

Package	Technologies considered	Peak BTE
Baseline	Representative Euro VI engine	45%
2017 best in class	Increase in compression ratio and injection pressure; reduction in EGR rates and accessories' management	46%
2020+	2017 best in class + reductions in friction and pumping losses; enhanced aftertreatment and turbo efficiency; turbocompounding	49%
2020+ with WHR	2020+ with a waste heat recovery system using an organic Rankine bottoming cycle instead of turbocompounding	51%
Long-term	Reduced parasitic losses, advanced injection and combustion strategies, improvements in the WHR system (Wall, 2014) Alternative pathways: opposed piston engine, low temperature combustion, dual fuel combustion and split cycle engines	55%

Table 2: technology packages. Source: ICCT study.

Technology potential fuel consumption reduction from engine technology is significant.
Transport & Mobility Leuven estimates that a 5% improvement is feasible by 2020 and up to 9% is technologically feasible. The Institute for Energy and Environmental Research (Heidelberg, Germany) estimates that the maximum technology potential by 2020 is 11%. The impact assessment of the European Commission estimates technology potential at 13.1%. The latter value was recently scrutinized by the Impact Assessment Institute (2016) and no adjustments were suggested, then we can assume it as realistic.
Table 3 shows the four engine technology steps and their corresponding fuel consumption reductions over the Regional Delivery and Long Haul cycles. Fuel consumption reductions of up to 9.5% can be obtained with currently available technologies. The addition of a waste heat recovery system, which is at an advanced stage of development, can achieve up to 11.7% fuel consumption reduction. The long-term engines are not yet available, but pathways to achieve such levels of efficiency (up to 18.1% fuel consumption reduction) have been identified.

Engine package	Regional		Long Haul	
	FC (L/100km)	FC reduction	FC (L/100km)	FC reduction
Baseline	36.37	–	33.06	–
2017 best in class	35.17	3.3%	31.97	3.3%
2020+	33.28	8.5%	29.91	9.5%
2020+ with WHR	32.32	11.1%	29.18	11.7%
Long-term	30.64	15.8%	27.07	18.1%

Table 3: fuel consumption reduction potential. Source: ICCT study.

2.2.1.2 LNG powered trucks

Heavy-duty liquefied natural gas (LNG) vehicles work much like gasoline-powered vehicles with a spark-ignited internal combustion engine. The natural gas is super-cooled and cryogenically stored in liquid form, usually in a tank on the side of the truck. LNG is typically a more expensive option than compressed natural gas (CNG), and is most often used in heavy-duty vehicles to meet range requirements. Because it is a liquid, the energy density of LNG is greater than CNG, so more fuel can be stored on board the vehicle. This makes LNG well-suited for Class 7 and 8 trucks traveling longer distances.

Liquefied natural gas (LNG) is the ideal alternative fuel for long-haul trucks. Since liquefied natural gas takes up just 1/600th the volume of natural gas in its gaseous state, enough fuel can be stored in the tank to travel the same distances as a diesel-powered vehicle.

LNG is currently the only profitable alternative fuel for heavy trucks. Switching to LNG has a direct positive impact on the climate, the environment and health. LNG-powered trucks are also significantly quieter, as shown in Figure 7.

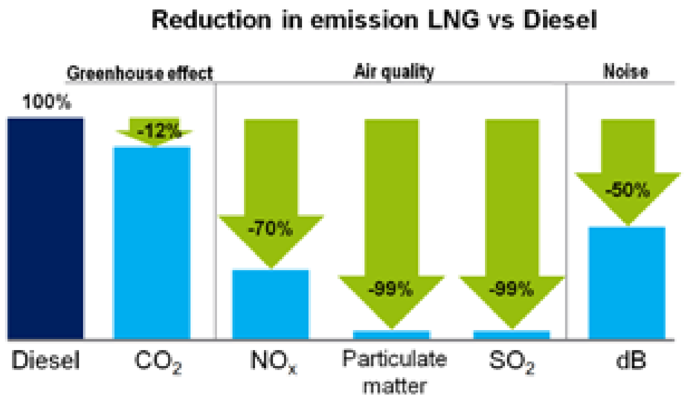


Figure 7: LNG vs Diesel trucks. Source: Fluxys.

The only barrier to the diffusion of LNG powered trucks is the high capital cost. Even though natural gas is significantly cheaper than diesel and is also more efficient, meaning that trucks consume less natural gas, a LNG-powered truck is significantly more expensive at this time. The additional cost for a truck with a bi-fuel engine can be paid back in around two years if the truck runs solely on LNG. If the truck runs on LNG just 60% of the time, and diesel 40% of the time, then the payback period is around 3.5 years.

2.2.1.3 Transmission and Driveline Technology

The transmission and driveline have the potential to reduce energy losses in several ways [4].
The areas of improvement considered for rigid trucks are mechanical efficiency of the driveline, engine-transmission integration, start-stop systems, and powertrain hybridization.

Mechanical Efficiency

The overall mechanical efficiency of the driveline is mainly comprised of the efficiencies of the main transmission and the axle drive.

On one side, there is the potential to improve transmission gear efficiency and to reduce losses related to the transmission lubrication systems (e.g., lubrication pump parasitic losses). Default input values for VECTO indicate average transmission efficiency of about 93% at indirect gears and about 96% at direct gear. Maximum values are about 96% for indirect gear and about 99% for direct gear. The ICCT study states that transmission manufacturers indicate values of 99.1% for indirect gears and 99.7% for direct gears for current best in class transmissions, while U.S. EPA and U.S. DOT (2016a) project that transmission efficiency could improve by 1% in

the timeline 2018‑2027. An increase of transmission efficiency by 1 percentage point brings a fuel consumption reduction of 0.9% in both the Regional Delivery and the Long Haul cycles.
On the other side, axle efficiency is improveable by reducing mechanical losses from the friction between mating gears as well as spin losses from axle rotation. Generally speaking, frictional losses are proportional to the torque on the axle and spin losses are a function of rotational speed of the axle. In fact, axle efficiency is sensitive to axle reduction ratio: rear axles with lower axle ratios are more efficient than rear axles with higher axle ratios. Default input values for VECTO indicate average axle efficiency of about 95% and maximum values of about 98%. In the ICCT study, it is assumed that improved axle gear designs and low friction axle lubricants contribute to 1 percentage point higher axle efficiency, for a resulting axle efficiency of 97%. Based on this assumption, the fuel consumption reduction from axle efficiency technology is 0.9% in the Regional Delivery cycle, and 1.3% in the Long Haul cycle.
To summarize, combining improved transmission and axle efficiency, a fuel consumption reduction of about 1,8% looks possible.

Engine-transmission integration Tractor Trailer

The integration between the engine and the transmission, referred to as deep powertrain integration or advanced shifting strategy, is a very effective way to reduce fuel consumption without sacrificing driving performance.
Engines and transmissions are managed by individual electronic controls: the engine control unit (ECU) and the transmission control module (TCM). Engine-transmission deep integration is “the combination of enhanced engine-transmission communication and advanced shifting strategies that optimize engine and transmission operation to achieve fuel consumption savings” [4]. Constant ratio steps and simplistic shifting controls can be enhanced, especially when co-optimized with the engine.
The final purpose of the transmission is to keep the engine operation locus as close as possible to its peak brake thermal efficiency: to do this, the ideal solution would be to have an infinite number of gears. Obviously, this is not feasible, but there are transmission systems that actually simulate the behavior of a gearbox with infinite gears, like the CVTs (Continuously Variable Transmission).
An estimation of the potential benefits of engine-transmission deep integration thus can result from the ratio of cycle-averaged thermal efficiency values against peak brake thermal efficiency values. With an ideal engine-transmission integration, the engine would operate 100% of the time at peak efficiency, resulting in a deep-integration ratio equal to 1.
The integration ratio of the rigid truck considered in the ICCT study is between 0.91 (for the Urban Delivery cycle) and 0.97 (Long Haul cycle). The corresponding maximum benefit for deep integration in rigid trucks then ranges between 3% and 9%. Because this potential cannot be fully tapped by transmissions with a finite number of gears, the ICCT study estimates the potential of engine-transmission integration in one-third of the aforementioned maximum theoretical benefit.
DCTs are a natural solution for powertrain deep integration, because the absence of torque loss during gear shifting eliminates the disadvantages of the higher shifting frequency of deeply integrated powertrains. In comparison to the baseline manual transmission, the gearbox and shifting automation results in a fuel consumption improvement of up to 1.9% (for the Urban Delivery cycle).
For the mid-term driveline package, the combined effectiveness of the deep integration of a DCT is estimated as 5.0% over the Urban Delivery cycle, 2.4% over the Regional Delivery cycle, and 0.8% over the Long Haul cycle.

Start-stop Rigid

Start-stop systems reduce fuel consumption by reducing the amount of engine idling during short vehicle stops, such as those frequently occurring in urban traffic.
In the ICCT study, the effectiveness of start-stop systems was estimated from the time fraction that the vehicle was at standstill over the cycle and the curb-idle fuel consumption from the engine fuel map. Given that this estimation corresponds to an upper boundary of the fuel consumption reduction, the effectiveness value was adjusted by a correction factor of 90% to account for the real-world behavior of start-stop systems and the additional auxiliary work during the driving phases. Based on the ICCT simulation results of the baseline rigid truck selected, start-stop systems resulted in a fuel consumption reduction of 4% over the Urban Delivery cycle, 0.9% over the Regional Delivery cycle, and 0.1% over the Long Haul cycle.

Hybrid powertrains

The fuel economy advantages of hybrid powertrains mainly comes from the ability to recover mechanical energy. The energy that might otherwise have been dissipated as heat through the wheel brakes is in fact converted to electricity by a generator and subsequently stored in a battery to provide traction power when needed. The amount of energy available for regenerative braking is highly dependent on the frequency of deceleration events and the fraction of downhill operation during the duty cycle. For example, Bosch designed a 120-kW parallel hybrid system for heavy-duty long-haul operations with a 2-kWh battery, featuring fuel consumption reductions of up to 6% with the potential of further efficiency benefits by electrification of accessories and/or downsizing of the diesel engine.
In regional and urban delivery, HGVs have a great potential for efficiency improvement through hybridization. The high share of braking and deceleration events in urban and regional traffic make them more suitable for regenerative braking. In the recent past, truck manufacturers in the European market sporadically launched hybrid powertrains with small batteries (<2 kWh) to exploit this potential. In all the cases, the electric motor was located between the clutch and the gearbox to be able to decouple the electric powertrain from the combustion engine on demand.
A limited amount of experimental fuel consumption values of hybrid vehicles is found in the literature; however, these values are difficult to compare due to their differences in vehicle types, payloads, and duty cycles. Transmission manufacturer Aisin reported results over several city test cycles that quantify the potential of hybridization at approximately 7%.
A simulation-based analysis at Oak Ridge National Laboratory in the United States estimated the potential fuel consumption reduction of a 16-tonne hybrid truck in comparison to its conventional counterpart at 36% during an urban driving cycle [4]. In highway operation the fuel consumption benefits of hybridization are reduced to approximately 3.5%. On-road investigations by FPInnovations on three 12-tonne hybrid vehicles showed a reduction in fuel consumption between 14.7% and 34.4% during specific pickup and delivery cycles, typical of urban operations.
Given the wide ranges of fuel consumption reduction found in the literature, and the strong dependence of these on the duty cycle, the ICCT study uses energy auditing to determine the regenerative braking potential. Using the braking power dissipation as an input, the post-processing algorithm calculates the energy recuperation through regenerative braking based on the hybrid powertrain specification.

Table 28 shows the fuel consumption reduction over the Urban Delivery, Regional Delivery, and Long Haul cycles of the hybrid powertrain (with start-stop) in comparison with the baseline rigid truck, and the non-hybrid rigid truck with the long-term vehicle, engine, and road-load technology packages.

Vehicle and powertrain package	Urban Delivery	Regional Delivery	Long Haul
FC reduction of hybridization applied to baseline technology package	17.3%	6.1%	2.3%
FC reduction of hybridization applied to long-term technology package	23.2%	9.4%	4.0%

Table 3: FC reduction from hybridization. Source: ICCT study.

A more detailed analysis of hybrid powertrains will be carried out in chapter 2.4.

2.2.1.4 Road Load Technologies

Similarly to what has been done with the engine, technology packages with increasing levels of road load reduction technology were evaluated by the ICCT. The following sections describe such packages in terms of aerodynamics, tire rolling resistance, and mass reduction.

Aerodynamics

Since aerodynamic drag is proportional to the square of the vehicle speed, aerodynamic devices are more effective in the long-haul cycle than in the urban low-medium speed operations. Anyway, it can still help to reduce overall fuel consumption.

According to a study conducted in 2015 by Frank Dünnebeil [8], a drag coefficient reduction of 10% from a baseline CD value of 0.55 is possible in the mid-term when using lateral panels on the cabin structure, rounded leading edge structure, side panels, and a 50-cm rear device. Based on that, a CD value of about 0.5 was assumed by ICCT in the mid-term package.

In another study from Landman [9] the performances of drag reduction configurations on a cab-over-engine rigid truck in a fullscale wind tunnel were analysed. The best configuration includes a valence, cargo box front treatment, boat tail, and side panels to achieve 23% aerodynamic drag reduction from a baseline of 0.58 (Landman, Cragun, McCormick, & Wood, 2011). Based on that, a CD value of 0.45 was assumed in the long-term package.

The fuel consumption reductions of such individual measures are listed at the end of this section.

Tires

The dissipation of energy is proportional to the tire rolling resistance coefficient, vehicle weight and speed. Technological advancements in low rolling resistance tire designs and materials are applicable to reduce rolling resistance losses. For example, a possible solution is wide-base single tires for the drive axle of rigid trucks: they feature a lower sidewall count (two sidewalls instead of four), which results in reduced energy dissipation in the deformation process and thus in a lower rolling resistance.

Proper tire inflation is also necessary to achieve the fuel efficiency benefits of low rolling resistance tires. Tires with low inflation pressure exhibit a larger footprint on the road, more sidewall flexing, and tread shearing: the consequence is a higher rolling resistance than tires operating at their optimal inflation pressure.

Nowadays, several systems are available to help to maintain the correct tire inflation pressure. Automatic tire inflation system (ATIS), which monitors tire pressure and automatically keeps tires inflated to a specific pressure, depending on the payload, are already on the market. Alternativiely, the tire pressure monitoring system (TPMS) notifies the operator of tire pressure but requires the operator to manually inflate the tires to the optimal pressure. However, these technologies were not considered in the study because it is assumed that tires are inflated to appropriate pressure at all times.
Consultants commissioned by the ICCT reported that tire development is ongoing and a rate of rolling resistance reduction of about 2% per year appears to be feasible. Ideally, this would generate reductions of about 27% by 2030. This annual reduction rate results to be consistent with several further scenario modeling results.
Current best available tires are Class B steer tires and Class C drive tires. Based on that, a CRR value of 5.6 was assumed by ICCT for the mid-term package.
Class A tires are forecast to be available for both steer and drive tires by 2030. Therefore, a CRR value of 4.0 was assumed for the long-term package.
The fuel consumption reductions of such individual measures are listed at the end of this section.

Mass reduction
The energy required to accelerate, overcome rolling resistance, and overcome road grades is proportional to the mass of the vehicle. Therefore, its reduction turns out to be an excellent strategy in the urban operations as they are composed by typical transient situations, exactly the ones that benefit most from a weight reduction. Reducing the vehicle curb weight can impact efficiency in different ways. For trucks that operate with maximum load factor (Garbage Collection..), lightweighting allows for an increase in the payload without changing the specific fuel consumption (units of L/100km). Instead, for trucks that are volume-constrained, weight reduction will not affect the payload but will lead to reduced fuel consumption as well as load-specific fuel consumption (L/km/t). Volume-limited operations are estimated to constitute between 10% and 19.5% of total operations in the European Union.
In their study [10], Hill et al. (2015) evaluated the potential of lightweighting as a measure to improve heavy-duty vehicles' fuel efficiency. The results show that a 5% curb weight reduction is possible by 2020 with available state-of-the-art options, which mainly include small design hanges to components, as well as an increased use of higher grade steels on the chassis, body, and suspensions. The study also shows that a 17% curb weight reduction is possible by 2030 mainly through material substitution of iron and steel by advanced high-strength steel and aluminum/magnesium for various components, as well as additional use of some composite materials.
The fuel consumption reductions of such individual measures are listed at the end of this section.

2.2.1.5 Vehicle Technologies

Advanced Driver Assistance Systems
The technologies grouped under advanced driver-assistance systems (ADAS) have mainly been developed for safety reasons; despite that, several ADAS bring also a reduction in fuel consumption, like the adaptive cruise control (ACC), predictive cruise control (PCC) and speed limiters. Anyway, ADAS specifically designed to reduce fuel consumptions are not missing. One example is the Eco-Roll, an advanced system designed by Scania: it calculates when a truck should use gravity to roll in neutral downhill, enabling a potential fuel costs saving of up to two percent.

ACC systems are an extension of traditional cruise control systems, where instead of maintaining a constant vehicle speed, the speed is adjusted to maintain a pre-set distance to the vehicle driving ahead. When following a skilled driver able to reduce unnecessary acceleration and deceleration events, fuel savings have been estimated at 1,9% [11].

Intelligent vehicle controls such as PCC and neutral coasting, also known as Eco-Roll, can also reduce the braking losses over a given cycle. Based on GPS elevation information, PCC systems optimize the shifting strategy, the vehicle velocity, and its acceleration to minimize the fuel consumption. They exploit the large mass of HDVs as an effective kinetic energy storage system. Basically, the PCC reduces the speed during uphill operation and then switches to neutral (Eco-Roll) during downslope driving [12]. Please notice that, with lower benefits, Eco-Roll systems are also available independently from PCC systems.

Lastly, speed-limiters can also bring significant fuel economy benefits due to the aerodynamic drag dependence on vehicle speed. Moreover, the driveline and transmission frictional losses, as well as the rolling resistance, also have a speed dependent component. The benefits of speed-limiters over the Regional Delivery, reducing vehicle speed from 85 km/h to 80 km/h, have been of 2,0%.

Accessories

Proper vehicle operation is dependent on a number of supporting systems, collectively known as vehicle accessories. Among them we find the power steering system, the cooling fan, the electric generator, the air compressor, and the air conditioning system. The power absorbed by these vehicle accessories has a direct toll on the fuel consumption performance of the vehicle. Similar to the already described engine accessories, the decoupling of the associated loads can reduce fuel consumption by engaging the loads on demand. Table 25 presents a summary of the technologies aimed at reducing the vehicle accessories' power. The potential for fuel consumption reduction from improvements in the accessories is dependent on the duty cycle. In the technical literature, the estimated potential varies between 1% and 8%. A maximum reduction of accessory energy demand of 50% is commonly assumed, resulting in 2.0% reduction over the Regional Delivery cycle.

Accessory	Fuel saving technology description
Power steering	Electrically Powered Hydraulic Steering (EPHS) reduces the power steering losses, particularly during idling and highway cycles. On-demand control of the hydraulic power steering system can also be done using on/off electromagnetic clutches.
Cooling fan	The demand-based control of the cooling fan can be achieved using several technologies such as on/off electromagnetic clutches, passive bimetallic viscous-couplings, electronically controlled viscous-couplings, and hydraulically powered systems.
Generator	Traditional DC current rectifiers of generators are based on a diode bridge. Diodes have an intrinsic voltage drop (~1 volt) that affects the generator efficiency. The use of semiconductor active rectifiers improves the generator efficiency from around 65% up to 80%.
Air compressor	Clutched air compressors reduce the losses associated with the off-period of the duty cycle (i.e., no pressure generation).
Air conditioning	Battery and all-electric air conditioning systems

Table 4: vehicle accessories technologies. Source: ICCT study.

2.2.1.6 Summary

2.2.1.6.1 Individual Technologies

The table below presents the summary of the individual technological improvements presented in the paragraphs above and their respective impact on fuel consumption over the Urban Delivery and the Regional Delivery, the two cycles employed in this work.

For the highly transient Urban Delivery cycle, the major benefits come by a reduction of the vehicle mass, the addition of start-stop, and, most notably, the integration with a hybrid powertrain.
For Regional Delivery cycles, improvements in the road load losses (rolling resistance and aerodynamic drag) produce the largest reductions.

Technology	Urban Delivery	Regional Delivery
Baseline fuel consumption	21.40 L/100km	20.02 L/100km
Mid-term engine (BTE = 43.1%)	2.3%	2.3%
Long-term engine (BTE = 44.4%)	5.1%	5.1%
Mid-term aerodynamics (C_D = 0.494)	3.0%	6.5%
Long-term aerodynamics (C_D = 0.45)	4.5%	9.6%
Mid-term tires (C_{RR} = 5.6 N/kN; classes B-C)	2.6%	2.9%
Long-term tires (C_{RR} = 4.0 N/kN; classes A-A)	6.2%	7.0%
Mid- and long-term transmission efficiency	0.8%	0.8%
Mid- and long-term axle efficiency	0.8%	0.8%
Mid-term lightweighting (-325 kg)	2.1%	1.4%
Long-term lightweighting (-1,105 kg)	6.8%	4.9%
Mid- and long-term accessory power consumption (reduction of 50%)	4.6%	2.8%
Start-stop (applied to baseline)	4.0%	0.9%
Hybrid powertrain (applied to baseline)	13.8%	5.3%

Table 5: individual technologies benefits. Source: ICCT study.

2.2.1.6.2 Technology Packages for Rigid Trucks

The main features of the mid-term and long-term technology packages can be found in Table 6. Please notice that, in both cycles, the payload modeled was 3 tonnes.

Technology	Mid-Term Package	Long-Term Package
Engine	Equivalent to EPA 2021	Equivalent to EPA 2027
Transmission	DCT with deep integration	Hybrid
Transmission	1% more efficient	Same as mid-term
Axle	1% more efficient	Same as mid-term
C_{RR}	5.6 (BC)	4.0 (AA)
C_D	0.5	0.45
Mass	(-325 kg)	(-1,105 kg)
Accessories	50% power demand	50% power demand
Others	Start-stop	Included in hybrid system
Package fuel consumption reduction Urban Delivery cycle	23%	43%
Package fuel consumption reduction Regional Delivery cycle	20%	36%

Table 6: technology packages for rigid trucks. Source: ICCT study.

The mid-term package includes technologies that are about to come on the market or already being sold by some manufacturers. The package includes an engine with 43.1% peak brake thermal efficiency and deep integration between engine and transmission with a DCT transmission. The transmission and axle frictional losses are reduced by 25%, resulting in an approximate increase in mechanical efficiency of 1%. Regarding road load technologies, the aerodynamic package includes cabin side panels and rounded leading edges on the cab. The rolling resistance coefficient corresponds to class C tires on the steering axle and class B tires in the drive axle. The curb vehicle mass is reduced by 5%, corresponding to 325 kg. The use of on-demand accessories results in an estimated 50% reduction of the parasitic loads. Lastly, the package features start-stop technology. The resulting fuel consumption reductions from baseline for the mid-term package are 23% for the Urban and 20% for the Regional Delivery.

The long-term package corresponds to an additional effort in the R&D activities of the truck and component manufacturers. Some of these technologies are only available in the demonstration stage, but are likely to be further developed and may be introduced to the market between 2025 and 2030. Such a package employs an engine with 43.9% peak brake thermal efficiency, mainly due to improvements in friction reduction, advanced turbocharging, and combustion control. The aerodynamic package includes, additionally to the mid-term package, cargo box front treatment, boat tail, and side panels, to achieve a drag coefficient of 0.45. The rolling resistance coefficient corresponds to class A tires in both the steering and drive axles. The curb vehicle mass is reduced by 1.1 tonnes, for a 17% reduction of the curb weight. Lastly, the long-term package features a parallel hybrid powertrain with the motor/generator placed between the clutch and the engine, with a 44-kW electric power and a 1.9-kWh battery. The resulting fuel consumption reduction from the longterm package is higher for the Urban Delivery cycle than the Regional Delivery cycle due to the higher effectiveness of the hybrid powertrain in urban transient conditions. The long-term package reduces fuel consumption by 43% for the Urban Delivery and by 36% for the Regional Delivery.

Figure 8 shows the same fuel consumption reduction potentials, with the individual contributions of the different technologies, for the technology packages presented by the ICCT study. Please note that the improvements attributed to different technology areas have been estimated: since technologies interact one with each other, it is not possible to isolate the contribution of one technology in a given technology package.

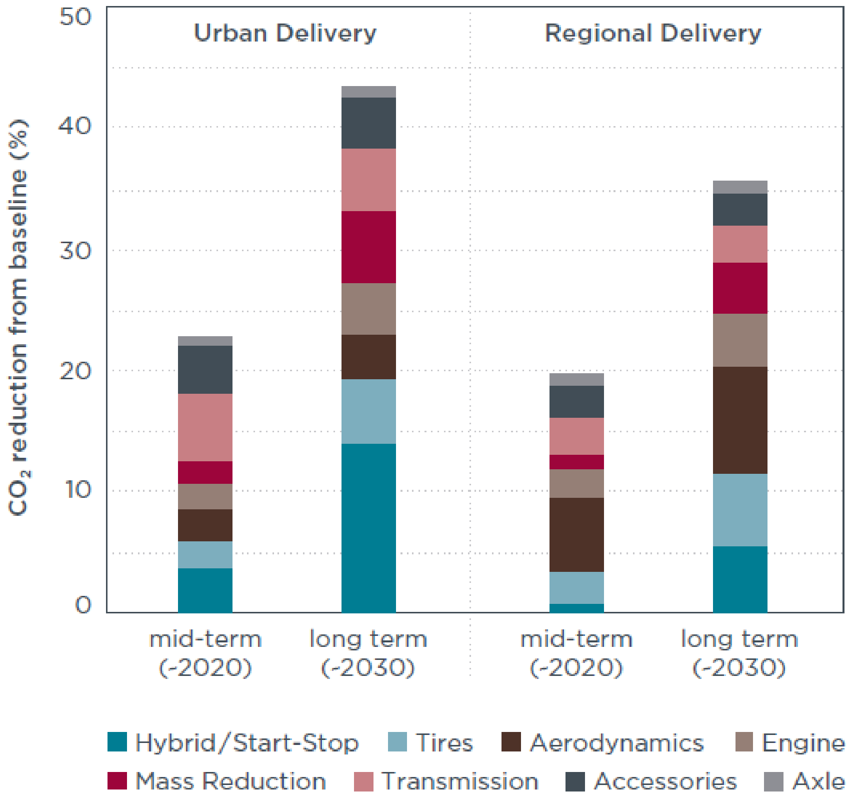


Figure 8: potential CO2 reduction from rigid truck technologies in the 2020-2030 timeframe over the VECTO Urban Delivery and Regional Delivery cycles. Source: ICCT study.

2.2.2 Electric Powertrains

2.2.2.1 Technical Overview

The EVs powertrain is composed by an electric drive system with a battery that servs as energy buffer. The electric machine, usually of three phase AC type, is connected to the wheels shaft via a gearbox and a differential. The energy is stored chemically in a battery which, is electrically connected to the machine by means of a DC/AC power electronic converter accompanied by a control system. The control system is in charge of controlling the frequency and magnitude of the three phase voltage applied to the electric machine on the basis of the driver's request, communicated via the acceleration and/or brake pedal.
In vehicle applications, it is usually desirable to keep the physical volume of the electric machine down. This can be done by designing it for higher speed levels. A reasonable compromise between volume and performance looks to be a maximum speed between 12000 to 16000 rpm [13]. Clearly, a reduction gear ratio towards the wheels is needed; moreover, in order to give the left and right traction wheels a chance to spin at slightly different speeds during turning,there is also a need for a differential to be connected between the wheels [14]. Often, the differential also includes a final gear ratio that, in the case of commercial vehicles, can be chosen on the basis of the mission. A typical BEV powertrain is depicted below.

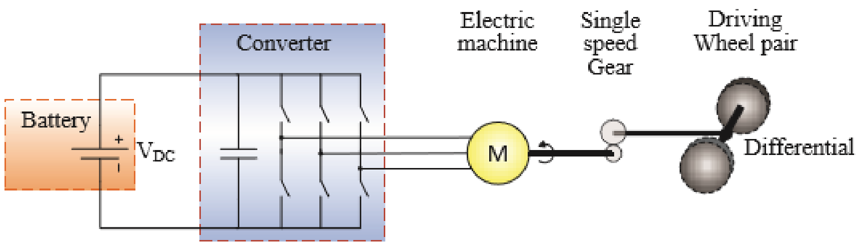


Figure 9: typical layout of a EV powertrain. Source: [14].

In the next sections the typical components of an EV powertrain are briefly analysed.

2.2.2.1.1 Battery

2.2.2.1.1.1 Battery Types and Arrangement Layouts

An electric battery stores and converts electrochemical energy to electrical energy.
The batteries used for powertrain applications are also called secondary batteries: while a primary battery has to be replaced after discharge, they are batteries that can be repeatedly charged and discharged.
A battery cell is the basic battery unit. In turn, a battery pack comprises multiple cells. Multiple cells are required to increase the energy storage, the pack voltage, or the battery pack power. Many electrical devices require higher voltages than the basic cell voltage for operation. For example, the speed of a dc electric motor, powered directly by a battery, is approximately proportional to the battery voltage.
The battery cells can be arranged in series (b) or in parallel (c).
Cells are arranged in series in order to generate a higher voltage, and higher power, as the battery pack voltage is simply the sum of the individual cell voltages.
Cells can also be arranged in parallel, in order to generate a higher output current and power. The stored energy, lifetime, and voltage of a battery depend on the current or power pulled from the battery. Adding more cells in parallel increases the energy, lifetime, and voltage for a given power.

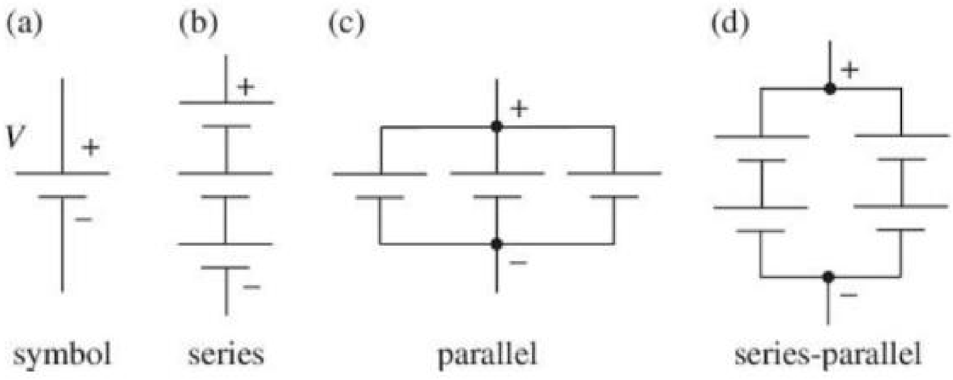


Figure 10: (a) battery symbol; (b) series layout; (c) parallel layout; (d) series-parallel layout. Source: [15].

EVs batteries are typically arranged in series-parallel (d), in order to obtain higher voltage, current, power, energy, and lifetime. For example, the 2012 Tesla Model S with an 85kWh battery pack has 16 modules in series. Each module has six strings of submodules in series with each sub-module having 74 cells in parallel. Thus, the battery pack has a total number of 7104 cells, effectively a matrix of cells with 96 in series and 74 in parallel. Many of the automotive battery packs have 96 Li-ion cells in series, and the battery pack voltage is close to 400 V as the no-load voltage on each Li-ion cell is just 4 V. The voltage level of 400 V is a typical value for many power converters, and many related technologies have been developed to efficiently and safely convert power at this voltage level [15].

2.2.2.1.1.2 Recent EVs and Battery Chemistries

The battery performances are strictly related to its chemistry. The material selection depends on design constraints (cost) but also on the application. For example, a Electric Vehicle (EV) battery is optimized for a wide operating range, while a Hybrid Electric Vehicle (HEV) is optimized for a narrow operating range in order to maximize the number of discharge cycles.

The General Motors (GM) EV1 electric car came to market in 1996 with a lead-acid battery pack. The lead made it a very heavy battery, thus limiting the on-vehicle energy storage. Furthermore, the chemistry has a relatively short lifetime, further reducing the energy storage as the capacity degrades. At that time, lead acid was the only available chemistry for vehicles; anyway, NiMH technology was being developed rapidly, and the second-generation GM EV1, launched in 1999, featured a NiMH battery pack. The advantages of NiMH over lead-acid chemistry are evident: NiMH has a greater energy capacity and longer lifetime than PbA. NiMH was also chosen by Toyota for its 1997 Toyota Prius.

In the meantime, Li-ion was being developed as the chemistry for cellular phones and laptops due to its large capacity and lifetime. Thanks to Li-ion chemistry, EVs had a second life with the launch of the Tesla Roadster in 2008. Lithium is the ligthest metal, and the Li-ion battery has many advantages over the other technologies: higher energy density, higher cell voltage, and longer life.

The family of Li-ion chemistry comprises several variations. Earlier Li-ion chemistries featured cobalt and manganese as main metals. The cathode is typically a mix of various metals. The mix and the choice of materials significantly influences the energy density, lifetime, safety, and cost of the battery.

For example, one of the most interesting electric vehicles on the market, the Tesla Model S, employs a Panasonic nickel-cobalt-aluminum (NCA) battery. In these batteries, nickel can typically make up 85% of the cathode with aluminum and cobalt making up 10% and 5% respectively. Thanks to the high nickel content, the battery shows a very high energy density and a long life.

On the other side, the 2011 Chevrolet Volt features a NMC cathode battery. NMC stands for nickel, manganese, and cobalt with the formula $LiNiMnCoO_2$. The metals are mixed at approximately 1/3 each. Altough the NMC chemistry has a lower energy density than NCA, NMC exhibits a lower cost and a longer life. It is worth to notice that with the new 2016 model the energy density has improved from 87Wh/kg to 101 Wh/kg.

Lastly, the AESC batteries in the 2011 Nissan Leaf feature a blend of manganese and nickel. In chemical terms, the cathode is a mix of $LiMnO_2O_4$ and $LiNiO_2$ [15].

It is clear that the choices of manufacturers depends on several constraints, the cost being the primary. Anyway, the world of batteries is in a rapid evolution, which makes hard to predict the most promising battery chemistry. It can be disrupted very easily whenever a new type/chemistry is discovered in material sciences with superior properties. Anyway, here below is visible a roadmap for Lithium-Ion batteries technology evolution.

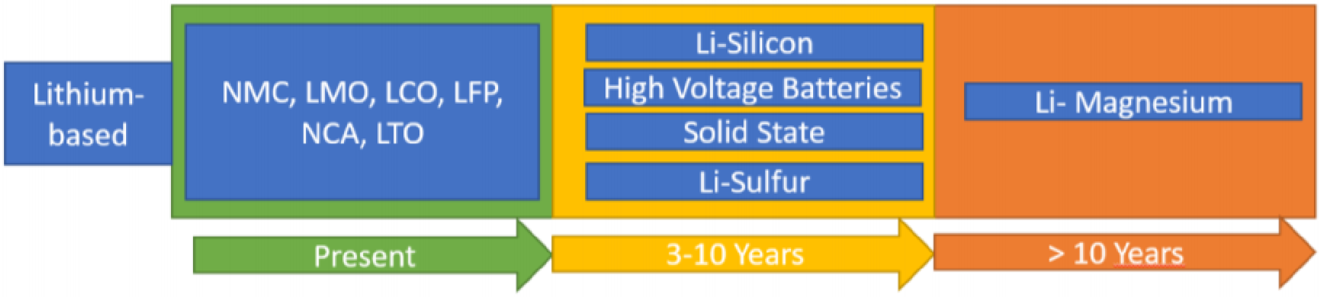


Figure 11: roadmap for Li-Ion batteries. Source: [16]

To make predictions further than a decade is extremely difficult but lithium-magnesium is worth mentioning. It has superior energy density and is abundantly available, but is still in a very early development phase.

It is interesting to summarize the published parameters of selected vehicles, from the 1996 GM EV1 on, in order to appreciate the developments in battery technology. The key parameters are presented in Table 6.

The 1996 GM EV1 had a vehicle weight of 1400 kg, of which over 500 kg was the battery pack. The rated energy and power of the battery pack were about 17 kWh and 100 kWh, respectively. The specific energy (Wh/kg) was relatively low at 34 Wh/kg, while the specific power (W/kg), was 200 W/kg. A common metric to compare batteries is to calculate the power to energy ratio, P/E, by dividing the specific power by the specific energy. Since HEVs need energy for a shorter time, the P/E ratio is usually low for EVs and higher for HEVs. The optimization for EV versus HEV operation can affect the ultimate battery chemistry as a particular battery can be optimized for energy (EVs) or power (HEVs). The 1996 GM EV1 lead-acid battery had a P/E of 6, a relatively high number for an EV pack compared to the next generation of EVs.

Vehicle	Vehicle weight (kg)	Battery weight (kg	Battery manufacturer	Chemistry	Rated energy (kWh)	Specific Energy (Wh/kg)	Cell/pack nominal voltage (V)	Rated power (kW)	Specific power (W/kg)	P/E ratio
1996 GM EV1	1400	500	Delphi	PbA	17	34	2/312	100	200	5,88
1999 GM EV1	1290	480	Ovonics	NiMH	29	60	1.2/343	100	208	3,47
1997 Toyota Prius	1240	53	Panasonic	NiMH	1.8	34	1.2/274	20	377	11,09
2008 Tesla Roadster	1300	450	Panasonic	Li-ion	53	118		185	411	3,48
2011 Nissan Leaf	1520	294	AESC	Li-ion	24	82	3.75/360	80	272	3,32
2011 Chevy Volt	1720	196	LG Chem	Li-ion	17	87	3.75/360	110	560	6,44
2012 Tesla Model S	2100	540	Panasonic	Li-ion	85	157		270	500	3,18
2017 Chevy Bolt	1624	440	LG Chem	Li-ion	60	136	3.75/360	150	341	2,51

Table 6: battery key parameters in automotive applications.

The introduction of NiMH technology to the GM EV1 in 1999 almost doubled the energy of the battery pack while slightly reducing the weight. Applying similar NiMH technology to the 1997 Toyota Prius HEV resulted in a battery with half the specific energy of the 1999 GM EV1 NiMH battery but with a much higher specific power as the battery is optimized for long-life hybrid applications. In regular operation, the 1997 Toyota Prius used only 20% of the available energy capacity in order to maximize its lifetime. The 1997 Toyota Prius P/E ratio is close to 11 versus 3 for the 1999 GM EV1 NiMH.

As already mentioned, the 2008 Tesla Roadster introduced the high-specific-energy Li-ion technology that allowed to reach a specific energy three to four times greater than that of the 1996 GM EV1 lead-acid battery and twice that of the 1999 GM EV1 NiMH battery, while having a higher specific power and a longer lifetime.

The 2012 Tesla Model S raised the specific energy and power to higher values featuring a battery pack almost five times bigger than the 1996 GM EV1 but with a similar weight.

The 2011 Chevrolet Volt features a HEV battery with a P/E of 9 and over double the specific energy of the 1996 GM EV1. The 2011 Nissan Leaf features a P/E close to 3 and a specific energy similar to the Chevrolet Volt.

The 2017 Chevrolet Bolt features a higher-power-density lower-cost battery pack than the 2011 Chevrolet Volt. The pack is shown in Figure 12. This GM vehicle illustrates the progress of battery technology as the 2017 Chevrolet Bolt has approximately four times the energy density of the 1996 GM EV1 at a fraction of the original cost.

Figure 12: battery pack of 2017 Chevrolet Bolt. Source: General Motors.

2.2.2.1.2 Converter

Onboard inverters apply pulse width modulation (PWM) control to convert direct current (DC) power stored in an onboard battery into alternating current (AC) power to drive the motor when drive power is needed. On the contrary, they apply an energy regenerating operation to charge the battery when power regeneration is needed. Since the available space in vehicles is very limited, automotive applications do require smaller inverters. For this reason, developing technologies enabling high power density for the main circuit of an inverter has been an ongoing task. At the same time, there is also demand for high-performance control circuit technology that provides specific functions such as drive torque control, motor speed control, and energy regeneration control. Moreover, by means of communication with vehicle controllers, they have to implement features such as anomaly detection, failure diagnosis, and the functional safety measures specified in ISO 26262. In order to realize these onboard application demands, innovations in high-voltage main circuits and high-performance control circuits, along with the evolution of the structural design technology used to mount these components in a compact package while enabling durable onboard applications that are resistant to vibrations and heat, are needed [17].

2.3.1.3 Electric Motor

Electric motors are machines which convert electrical energy into mechanical energy. rely on electromagnetic induction, a phenomenon discovered in the early 1800s by physicist Michael Faraday. He found that moving a magnet through a toroid, around which he had wrapped a conducting wire, generated an electric current in the wire. Electric motors use this idea, but in reverse: when a current passes through a coil, the coil becomes magnetized, and if it is connected to a shaft and suspended in the field generated by a permanent magnet, the opposing magnetic forces create enough force to turn the shaft. Connecting the shaft to a gear mechanism makes it capable of doing work. Moreover, the addition of bearings reduces friction and increases the efficiency of the motor.

The main parts of an electric motor include the stator and rotor, a series of gears or belts, and bearings to reduce friction. In case of DC motors, a commutator is also needed to reverse current direction every half turn and keep the motor spinning.

In modern commercial electric motors permanent magnets are usually replaced by electromagnets. A series of small coils arranged in a circular arrangement forms the stator, and these coils generate a standing magnetic field. A separate coil wrapped around an armature and attached to a shaft forms the rotor, which spins inside the field. Since it is not possible to attach wires to a spinning coil, the rotor usually features metallic brushes that remain in contact with a conducting surface on the stator. This surface, along with the stator windings, is connected to power terminals located on the motor housing [18].

2.2.2.2 Electric Trucks

Electric trucks are something only partially new. In fact, already in 2016 the swiss company E-Force unveiled its first full electric truck, the E-Force One AG, with a range of 300 km with a single charge.
E-Force built this electric 18-ton truck for regional and municipal retailers. The company has already won clients such as Feldschlösschen and Coop, who have E-Force trucks in their fleets.

In early 2017, Man presented its e-Truck, the first electric truck featuring a modular battery pack to adjust autonomy (and weight) on the basis of the mission. In fact, "the energy for the Man eTrucks is supplied by high-performance lithium-ion batteries from the Volkswagen Group. They are fitted below the cab, above the front axle, and on the left- and right-hand side of the frame, depending on the range requirements".

In late 2017 the californian automaker Tesla founder Elon Musk showed to the world the "Tesla Semi". Tesla founder Elon Musk said it will be capable of up to 800 km thanks its massive battery of 900 kWh. With such a massive battery it would be interesting to know which payload it is capable of, but unfortunately the value has not been released yet.

In 2018 european giants Daimler and Volvo unveiled their first full electric trucks.
Daimler group, through its two brands Mercedes and FUSO, presented two urban trucks. The Mercedes eTruck features a 220 kWh Lithium-ion battery that guarantees a range of 200 km. The E-Fuso Vision 1 is a smaller truck with a wider range: 23 tons of GCW with a 300 kWh battery pushing it for an impressive range of 350 km.
Volvo also unveiled its electric lineup, made of two vehicles with different scopes. The smaller one, the Volvo FL Electric, shows a 16-ton GCW and a range of 300 km; the bigger one, the Volvo FE Electric, has a GCW of 27 tons and a range of 200 km. Also in this case, no payloads have been released yet.

Apart from the E-Force, that is already on the market, all the mentioned trucks will hit the market in the next years. For this reason, only partial technical characteristics have been unveiled.
The up-to-date available informations are resumed in the table below.

Manufacturer	Truck	GVW [t]	Payload [t]	Max Battery Capacity [kWh]	Range [km]	Recharge time [h]	Commercialization	Specific Consumption [Wh/km/t]
E-Force	E-Force One AG	18	10	240	300	6	on the market	44,4
Tesla	Tesla Semi*	36,2		900	800	0,5 (80%)	2019	31,1
Volvo	Volvo FL Electric*	16		300	300	1,5/10 (DC/AC)	2019	62,5
	Volvo FE Electric*	27		300	200	1,5/10 (DC/AC)	2019	55,6
Daimler	Mercedes eTruck	26	12,8	220	200	2,5	2020	42,3
	E-Fuso Vision 1	23	11	300	350		2022	37,3
Man	Man eTruck*	18		160**	200		2021	44,4

*multiple battery options
**estimated

Table 7: technical caracteristics of presented E-Trucks.

2.2.3 Hybrid Powertrains

Hybrid vehicles, by definition, have two distinct power sources: a combustion engine and an alternative motive power source that is usually either electric or hydraulic motor(s). Hybrid powertrains can feature different layouts: the combustion engine can be coupled with the alternative power source to both provide tractive power to move the vehicle as in a parallel hybrid system. The combustion engine can also be designed to act as a generator to provide electrical energy to the electric motor, which in turn provides the sole tractive power to move the vehicle as in a series hybrid system. Hybrid vehicle technology was first developed and commercialized in the light-duty sector back in the early 2000’s.
After several years of development, medium- and heavy-duty hybrids, while still at low volume production, are now available.

2.2.3.1 Degree of Hybridization

Heavy-duty hybrid vehicles can be designed with various degrees of hybridization, ranging from very minimal to very extensive integration of hybrid components into the vehicle. Such a range reflects a spectrum of electrification, ranging from a few percent to greater than 50 percent of a vehicle's power requirements, as well as a progression of increasing vehicle weight and cost. The degree of hybridization is generally grouped into three categories, from least to most reliance on alternative power source: micro hybrids, mild hybrids and full hybrids.

1. Micro hybrid

Micro Hybrid vehicles feature a small electric motor that is designed just to provide start/stop function for the combustion engine and to recharge, acting as a generator, during regenerative braking events. The electric motor in this hybrid category is the smallest of the three designs since it does not provide any tractive power. Among the advantages, the design is the least intrusive, as it imposes minimal alterations to the conventional powertrain. Moreover, micro hybrids bring the lowest incremental cost and the smallest weight penalty of the three degrees of hybridization. However, because of the low level of hybridization, fuel economy improvement over conventional vehicle is also the least of the three hybrid designs, typically reaching a maximum reduction of not more than 10 percent.

2. Mild hybrid

In addition to the features found in micro hybrids, mild hybrid designs provide a greater level of regenerative braking capability, larger batteries, and more sophisticated controllers to manage energy flow. In this design, the electric motor also provides supplementary tractive power to the combustion engine when needed, as in acceleration events, and may also provide a limited range of electric-only operation. Due to the added features, the electric motor in a mild hybrid needs to provide more power than in a micro hybrid, leading to larger size and weight. The increased power of the electric motor also demands a larger battery, further increasing weight, and cost. The combustion engine in a mild hybrid system is usually kept at the same size and specifications as in an equivalent conventional vehicle. As a result, a mild hybrid design is heavier and more costly to be produced than a micro hybrid design. However,mild hybrids can ensure greater fuel economy improvement, generally 10 percent to 20 percent over a conventional vehicle.

3. Full hybrid

Full hybrid designs represent the most extensive integration of hybrid components into a conventional vehicle. The electric motor(s) in a full hybrid design has a prominent role as a tractive power source, either partially in the case of a parallel hybrid design or fully in a series hybrid design. The electrical system is capable of powering all vehicle electrical accessories, potentially including auxiliary components that are traditionally mechanically driven. Full hybrids require much larger battery packs and electric motor(s). Weights and costs are the highest of the three hybrid designs and the level of engine and hybrid system integration and control electronics is the most sophisticated. With this design, the design is rather intrusive and may require structural changes of the body. Anyway, the benefits of a full hybrid design are the greatest level of fuel economy benefit of the three designs, typically 20 percent to 50 percent. Full hybrids also provide a direct path to a plug-in HEV design, as well as providing a catalyst for innovations toward zero and near-zero technologies for heavy-duty vehicles [19].

2.2.3.2 Hybrid Architectures

Three main hybrid architectures are available for heavy-duty vehicle applications: parallel hybrid, series hybrid and, to a lesser extent, series-parallel hybrid. Each design has its own advantages and limitations and could be designed to ideally serve specific applications. All these hybrid architectures, employed in either full or mild hybrid designs, share some common elements:

- A drivetrain, typically involving an ICE and an electric motor(s) that can recover and reuse energy in addition to the main engine;
- An energy storage system;
- Control electronics;
- Regenerative braking.

The main differences among these hybrid designs is the relative size of drive train components, energy storage system and the level of interaction of the motive power source(s) with the drive wheels [19].

1. Parallel hybrid

In a parallel hybrid design, both the ICE and the electric motor have direct, independent connections to the transmission. This means that both of them can be used to accelerate the vehicle. By means of mechanical devices, such as torque couplers through gearbox differential, or speed couplers through planetary gear, the

torques and speeds from each motive source can be added or decoupled. A parallel hybrid system is often designed in such a way that the ICE provides power at cruising or high speed regimes, where it is most efficient, and the electric motor provides power during stop-and-go operations and at low speeds. Both power sources would typically be designed to operate together during accelerations.
A parallel hybrid system typically requires a lower level of integration with the existing vehicle drivetrain compared to a series hybrid and thus could be more easily adapted as a retrofit, in addition to new original equipment manufacturer (OEM) vehicles. Because the ICE provides power during cruising and high speed operation, the energy storage system in a parallel hybrid design results smaller than in a series hybrid design. Moreover, since in a parallel hybrid the electric motor does not have to be sized to provide 100 percent of the tractive power requirements, can be smaller. These batteries and electric motor sizing factors have the direct benefits of reducing cost and weight.
The reduction in overall vehicle weight, combined with the efficiency of the ICE when operated at largely steady-state, high speed conditions make the parallel hybrid system well-suited to improve the fuel economy of higher speed, long-haul operations vehicle; it not as efficient if operated in stop-and-go operation due to the transient load demands placed on the engine [19].

2. Series hybrid

In a series hybrid design, the engine is not directly linked to the transmission or the drive wheels. In fact, the energy produced from the ICE is converted to electric power by the generator which re-charges the energy storage device in order to provide power to one or more electric motors. The electric motor is then the only responsible for providing tractive power. Since the ICE does not follow the load requirements of the vehicle, it can be operated at its most optimum points in its speed-torque map, regardless of vehicle speed and load. This has two direct benefits, oxides of nitrogen (NOx) emission control and zero-emission potential. Also, since the engine is not asked to vary its power output to follow the vehicle transient load requests, NOx emissions from the diesel engine are more easily addressed. The engine can also be switched-off for temporary all-electric operations.
Since the electric motor in a series hybrid system is the only source of tractive power, it must be significantly larger than in a parallel hybrid system for equivalent vehicle power requirements. In addition, the battery pack must necessarily be larger as well. The resulting added weight and cost for motors and batteries are the main drawbacks in a series hybrid design. Anyway, the added weight is partially offset through the elimination of the transmission and, potentially, other driveline components, such as drive shaft and differential, reducing complexities and mechanical losses.
A series hybrid power train is well-suited for stopand-go, highly transient operations, such as transit bus and refuse hauler duty cycles. This design is not as efficient for sustained high speed or cruising operations, compared to parallel hybrid design, due to the sustained high energy demand that would be placed on the electric motor and energy storage system [19].

3. Series-parallel hybrid

In a series-parallel design, the tractive power is provided by either the ICE, or the electric motor, or both. This hybrid design combines the best aspects of series and parallel hybrids for vocational applications: utilizing the series hybrid advantage at low speed and the parallel hybrid advantage at higher speeds through the use of power split and/or electronic controller. In low speed operation the ICE is turned off and electric motor propels the vehicle. In normal operation, the power produced by the ICE is split, providing tractive power and generating electricity. In this mode, the electric motor also assists with tractive power or to generate electricity for recharging the batteries during regenerative braking. Under full-throttle or high-speed operation, the battery provides extra energy. This design is well-suited for mixed applications feautirng both stop-and-go, city driving and high constant speed, highway driving. The only disadvantage of this design can be found in the added complexity of the design and control electronics for power management, added components, and larger energy storage system (compared to a parallel hybrid). Series-parallel hybrid architectures are in a early phase of development [19].

2.2.3.3 Hybrid Categories

1. Hybrid-electric

Hybrid electric was the first hybrid platform developed for the heavy-duty vehicle sector. This platform still represents the most commercialized platform for vehicles across a wide range of vocational duty cycles. A hybrid electric heavy-duty vehicle can make use of any of the three major hybrid architectures described in the previous section. HEVs are currently available for a broad spectrum of missions, including food and beverage, parcel delivery, transit buses. The major components of a HEV include: an ICE, one or more electric motors, generator, power inverter, an energy storage system (batteries, ultra-capacitors), control modules, and mechanical coupling devices. The sizing of the components and the level of control complexity depends on the hybrid design and the level of hybridization desired.

2. Hydraulic

Hydraulic hybrid technology for HDV application is relatively new compared to hybrid electric technology, but is making rapid advances and is proving to be an ideal technology for certain high power demand, stop-and-go applications like shuttle buses and city transit buses. HHVs can be designed in any of the three common hybrid architectures, but is mainly employed in the parallel and series configurations. The basic components of a hydraulic hybrid include: an ICE, one or more hydraulic pumps/motors, accumulators and reservoirs, and hydraulic control modules. Energy storage is performed via hydro-pneumatic accumulators, where a hydraulic fluid is pumped into a high-pressure accumulator and compresses an inert gas, typically nitrogen. To provide tractive power, energy is then released through the expansion of the inert gas, pushing the hydraulic fluid through the actuator through hydraulic motor(s) and into a lowpressure reservoir. Tractive power in a hydraulic hybrid system can come from both the engine and the hydraulic motor in case of a parallel hybrid, or only via the hydraulic motor(s) in case of a series design. The energy necessary to charge up the high-pressure accumulator can come from either the engine or the hydraulic pumps, through regenerative braking, for either parallel or series design [19].
The main feature of a hydraulic hybrid system is that it exhibits a very high power density, defined as the maximum amount of power that can be supplied per unit mass or volume, and relatively low energy intensity, defined as the amount of energy stored per mass or volume. It follows that a hydraulic hybrid system perfectly fits for heavy applications that have very high power demand over short periods, like stop-and-go duty cycles. On the contrary, because of its low energy density, hydraulic hybrids are not suitable for applications that require long-distance, high-speed duty cycles, such as long haul trucks or regional carriers that have extended periods of highway cruising operations.
Another major characteristic of HHVs is their higher efficiency in kinetic energy recover from braking, compared to a hybrid electric system. For this reason, also brake wear is dramaticly reduced.
As a result, cost savings due to reduced brake maintenance intervals are significantly positive.

3. Plug-in

Plug-in hybrid electric vehicles (PHEVs) differ from conventional hybrids since they can be recharged from an external charger that is connected to the power grid. Clearly, the power grid offers a cleaner way to recharge the vehicle, compared to an ICE: for this reason, well-to-wheel (WTW) emissions are even further reduced. This external charging in addition to larger battery packs allows for extended all-electric driving range. There are two operation modes for PHEVs: charge depleting mode and charge sustaining mode. Charge depleting mode is when the vehicle operates exclusively on electric power (all-electric range). Charge sustaining mode is when the vehicle combines the two power sources for operation. Currently, in the truck market most of the PHEV development is occurring in the medium-duty sector, primarily in the utility truck application, where trucks require work site power and have shorter daily routes [19]. Utility trucks usually spend a significant amount of their time and fuel while idling at a work site utilizing an external electric power take off (PTO) to perform the job at hand. An ePTO provides energy to power the truck's hydraulic boom along with auxiliary equipment, emergency lights, and heating and air conditioning of the cabin. The benefits are clear: an ePTO eliminates works site idling, saves fuel and reduces noise which in turn improves safety by enabling better communication between workers and reducing potential hearing damage. Furthermore, the noise reduction also allows workers to extend their work days in areas with noise ordinances.

4. Catenary

A catenary-powered hybrid vehicle (CHV) is a HEV with the ability to access overhead catenary wires for propulsion power through the use of a pantograph. A CHV differs from pure electric catenary-powered vehicles, since it can operate with unlimited zero emission range when connected to the overhead catenary wires, but can also operate outside of the catenary system as a fuel efficient HEV when further range is needed, as in long haul applications. The main advantage is that this technology allows zero emission operations in targeted dense urban areas, exactly where emissions and noise reductions are most needed. Pure electric catenary-powered HDVs are a proven technology and already exist in many public transportation systems (trolley, light rail, city buses) and mining applications. While there are many benefits related to this technology, it is also important to note some potential concerns regarding the catenary infrastructurein particular space constraints and visual pollution or visibility. The CHV concept is currently being demonstrated and tested in Germany, close to Frankfurt, with the Siemens catenary system, the “eHighway”.

2.3 EU Regulations

2.3.1 Regulatory Framework

European emission regulations for new heavy-duty diesel engines are commonly referred to as Euro I ... VI. The emission standards apply to all the vehicles with a “technically permissible maximum laden mass” over 3,500 kg, equipped with compression ignition engines or positive ignition natural gas (NG) or LPG engines.

The regulations were originally introduced by the Directive 88/77/EEC, followed by a number of amendments. In 2005, the regulations were re-cast and consolidated by Directive 05/55/EC. From the Euro VI stage, the legislation has been simplified, as “directives”—which need to be transposed into all of the national legislations—were replaced by “regulations” which are directly applicable [20]. From the article [20] are also reported some of the most important steps in the heavy-duty engine regulations:

- Euro I standards were introduced in 1992, followed by the introduction of Euro II regulations in 1996. These standards applied to both truck engines and urban buses. The urban bus standards, however, were voluntary.

- In 1999, the EU adopted Directive 1999/96/EC, which introduced Euro III standards (2000), as well as Euro IV/V standards (2005/2008). This rule also set voluntary, stricter emission limits for extra low emission vehicles, known as “enhanced environmentally friendly vehicles” or EEVs.
- In 2001, the European Commission adopted Directive 2001/27/EC, which prohibits the use of emission “defeat devices” and “irrational” emission control strategies, which reduce the efficiency of emission control systems when vehicles operate under normal driving conditions to levels below the ones operated during the emission testing procedure.
- Directive 2005/55/EC, adopted in 2005, introduced durability and on-board diagnostic (OBD) requirements, as well as re-stated the emission limits for Euro IV and Euro V which were originally published in 1999/96/EC. In a “split-level” regulatory approach, the technical requirements pertaining to durability and OBD—including provisions for emission systems that use consumable reagents—have been described in the Commission Directive 2005/78/EC.
- Euro VI emission standards were introduced by Regulation 595/2009, with technical details specified in a number of ‘comitology’ packages. The new emission limits, comparable in stringency to the US 2010 standards, became effective from 2013/2014. The Euro VI standards also introduced *particle number* (PN) emission limits, stricter OBD requirements and a number of new testing requirements—including off-cycle and in-use PEMS testing.

2.3.2 Emission Standards

The following tables contain a summary of the emission standards and their implementation dates. Please notice that the dates in the tables refer to *new type approvals*—the dates for all vehicles are in most cases one year later.

There are two sets of emission standards, with different type of testing requirements:

- Steady-State Testing: Table 8 lists emission standards applicable to diesel (compression ignition, CI) engines only, with steady-state emission testing requirements.
- Transient Testing: Table 9 lists standards applicable to both diesel and gas (positive ignition, PI) engines, with transient testing requirements.

Stage	Date	Test	CO	HC	NOx	PM	PN	Smoke
			g/kWh				1/kWh	1/m
Euro I	1992, ≤ 85 kW	ECE R-49	4.5	1.1	8.0	0.612		
	1992, > 85 kW		4.5	1.1	8.0	0.36		
Euro II	1996.10		4.0	1.1	7.0	0.25		
	1998.10		4.0	1.1	7.0	0.15		
Euro III	*1999.10 EEV only*	ESC & ELR	*1.5*	*0.25*	*2.0*	*0.02*		*0.15*
	2000.10		2.1	0.66	5.0	0.10[a]		0.8
Euro IV	2005.10		1.5	0.46	3.5	0.02		0.5
Euro V	2008.10		1.5	0.46	2.0	0.02		0.5
Euro VI	2013.01	WHSC	1.5	0.13	0.40	0.01	8.0×10^{11}	
a - PM = 0.13 g/kWh for engines < 0.75 dm^3 swept volume per cylinder and a rated power speed > 3000 min^{-1}								

Table 8: EU Emission Standards for Heavy-Duty Diesel Engines: Steady-State Testing. Source: [20].

Stage	Date	Test	CO	NMHC	CH_4[a]	NOx	PM[b]	PN[e]
			g/kWh					1/kWh
Euro III	*1999.10 EEV only*	ETC	*3.0*	*0.40*	*0.65*	*2.0*	*0.02*	
	2000.10		5.45	0.78	1.6	5.0	0.16[c]	
Euro IV	2005.10		4.0	0.55	1.1	3.5	0.03	
Euro V	2008.10		4.0	0.55	1.1	2.0	0.03	
Euro VI	2013.01	WHTC	4.0	0.16[d]	0.5	0.46	0.01	6.0×10^{11}

a - for gas engines only (Euro III-V: NG only; Euro VI: NG + LPG)
b - not applicable for gas fueled engines at the Euro III-IV stages
c - PM = 0.21 g/kWh for engines < 0.75 dm^3 swept volume per cylinder and a rated power speed > 3000 min^{-1}
d - THC for diesel engines
e - for diesel engines; PN limit for positive ignition engines TBD

Table 9: EU Emission Standards for Heavy-Duty Diesel and Gas Engines: Transient Testing. Source: [20].

Additional provisions of the Euro VI regulation include:

- An ammonia (NH_3) concentration limit of 10 ppm for diesel (WHSC + WHTC) and gas (WHTC) engines.
- A maximum limit for the NO_2 component of NOx emissions may be defined at a later stage.

Test Cycles. The regulatory emission test cycles have been changed several times, as indicated in Table 8 and Table 9. Since the Euro III stage (2000), the old steady-state engine test ECE R-49 has been replaced by two cycles: the European Stationary Cycle (ESC) and the European Transient Cycle (ETC). Smoke opacity was measured over the European Load Response (ELR) test. The following testing requirements applied:

- Euro III: (1) ESC/ELR test for conventional diesel engines, (2) ESC/ELR + ETC testing for diesel engines with “advanced aftertreatment” (NOx aftertreatment or DPFs) and for EEVs, and (3) ETC test for positive ignition (NG, LPG) engines.
- Euro IV-V: (1) ESC/ELR + ETC testing for diesel engines, and (2) ETC test for positive ignition engines.

Since the Euro VI stage, diesel engines are tested over the WHSC + WHTC tests, while positive ignition engines are tested only over the WHTC.

Off-Cycle Testing. Euro VI regulation introduced off-cycle emissions (OCE) testing requirements. OCE measurements, performed during the type approval testing, follow the NTE (not-to-exceed) limit approach. A control area is defined on the engine map (there are two definitions, one for engines with a rated speed < 3000 rpm, and another for engines with a rated speed ≥ 3000 rpm). The control area is divided into a grid. The testing involves random selection of three grid cells and emission measurement at 5 points per cell.

In-Service Conformity Testing. Euro VI regulation also introduced in-use testing requirements that involve field measurements using PEMS. The testing is conducted over a mix of urban (0-50 km/h), rural (50-75 km/h) and motorway (> 75 km/h) conditions, with exact percentages of these conditions depending on vehicle category. First in-use test should be conducted at the time of type approval testing.

Emission Durability. Effective 2005.10/2006.10, manufacturers should also demonstrate that engines comply with the emission limit values for useful life periods which depend on the vehicle category, as shown in Table 10.

Vehicle Category†	Period*	
	Euro IV-V	Euro VI
N1 and M2	100 000 km / 5 years	160 000 km / 5 years
N2 N3 ≤ 16 ton M3 Class I, Class II, Class A, and Class B ≤ 7.5 ton	200 000 km / 6 years	300 000 km / 6 years
N3 > 16 ton M3 Class III, and Class B > 7.5 ton	500 000 km / 7 years	700 000 km / 7 years
† Mass designations (in metric tons) are "maximum technically permissible mass" * km or year period, whichever is the sooner		

Table 10: Emission Durability Periods. Source: [20].

Effective 2005.10/2006.10, type approvals require confirmation of the correct operation of the emission control devices during the normal life of the vehicle under normal conditions of use ("conformity of in-service vehicles properly maintained and used").

Incentives. EU Member States are allowed to use tax incentives in order to speed up the marketing of vehicles meeting new standards ahead of the regulatory deadlines. Such incentives have to comply with the following conditions:

- they apply to all new vehicles offered for sale on the market of a Member State which comply in advance with the mandatory limit values set out by the Directive,
- they cease when the new limit values come into effect
- for each type of vehicle they do not exceed the additional cost of the technical solutions introduced to ensure compliance with the limit values.

Euro VI type approvals, if requested, must have been granted from 7 August 2009, and incentives could be given from the same date. Euro VI incentives can also be given for scrapping existing vehicles or retrofitting them with emission controls in order to meet Euro VI limits.

Early introduction of cleaner engines can be also stimulated by such financial instruments as preferential road toll rates. In Germany, road toll discounts were introduced in 2005 which stimulated early launch of Euro V trucks [20].

Defeat Strategies. For Euro IV and V heavy-duty engines, an 'auxiliary emission control strategy' (AECS) is defined as

"an emission control strategy that becomes active or that modifies the base emission control strategy for a specific purpose or purposes and in response to a specific set of ambient and/or operating conditions, e.g. vehicle speed, engine speed, gear used, intake temperature, or intake pressure."

Also a 'base emission control strategy' (BECS) is defined as

"an emission control strategy that is active throughout the speed and load operating range of the engine unless an AECS is activated."

An AECS can be activated to protect the engine or vehicle from damage, operational safety, to prevent excessive emissions and to trade-off the control of one regulated pollutant for another. An AECS should not be used under the following conditions unless there is a critical need to do so:

- altitude below 1,000 meters (or equivalent atmospheric pressure of 90 kPa) and
- an ambient temperature between 2 °C to 30°C and
- engine coolant temperature between 70°C to 100 °C.

A 'defeat strategy' is defined as:

"an AECS that reduces the effectiveness of the emission control relative to the BECS under conditions that may reasonably be expected to be encountered in normal vehicle operation and use", or

"a BECS that discriminates between operation on a standardized type-approval test and other operations and provides a lesser level of emission control under conditions not substantially included in the applicable type-approval test procedures", or

"an OBD or an emission control monitoring strategy that discriminates between operation on a standardized type-approval test and other operations and provides a lower level of monitoring capability (timely and accurately) under conditions not substantially included in the applicable type-approval test procedures";

Please note that the term 'emission control system' is not used in the definition of defeat device as is the case for light-duty vehicles.

Full documentation of AECS and BECS details are required to be submitted upon application for certification.

For Euro VI heavy-duty engines, the terms Auxiliary Emission Strategy (AES) and Base Emission Strategy (BES) are adopted with similar definitions to AECS and BECS. The definition for 'defeat strategy' was changed to:

"an emission strategy that does not meet the performance requirements for a base and/or auxiliary emission strategy".

The reasons for using a AES remained similar to those for Euro IV and V vehicles. However, the envelope of conditions under which an AES should not be used are not clearly spelled out. Rather, the vehicle is required to meet OCE and in-use PEMS testing requirements. Full documentation of AES and BES details are required to be submitted upon application for certification [20].

2.3.3 Introduction of CO_2 Measurement

Despite the economic importance of fuel consumption, CO2 emissions from HDVs are currently neither measured nor reported. The European Commission started to work about it some years ago, developing a computer simulation tool, VECTO, to measure CO2 emissions from new vehicles.

With the support of this tool the Commission in 2015 proposed a legislation which would have required CO2 emissions from new HDVs to be certified, reported and monitored.

After the Legislative proposal made in 2017, on 17^{th} May 2018 the European Commission presented a legislative proposal setting the first ever CO2 emission standards for heavy-duty vehicles in the EU.

The proposal also includes a mechanism to incentivise the uptake of zero- and low-emission vehicles, in a technology-neutral way.

Benefits. The proposal will:

- contribute to the achievement of the EU's commitments under the Paris Agreement,
- reduce fuel consumption costs for transport operators – mostly medium-sized enterpirses (SMEs) – and consumers,
- help to maintain the technological leadership of EU manufacturers and suppliers.

Expected benefits include:

- Around 54 million tonnes of CO_2 reduced in the period 2020 to 2030 – equivalent to the total annual emissions of Sweden.
- Savings at the pump amounting to around €25 000 in the first 5 years of use for a new lorry bought in 2025 and up to about €55.000 in the first 5 years of use for a new lorry bought in 2030.
- Oil savings of up to 170 million tonnes of oil over the period 2020 to 2040 – worth around €95 billion at today's prices.
- GDP increases resulting in the creation of around 25 000 new jobs in 2025 [21].

CO_2 emission reduction targets. In 2025, the average CO2 emissions of new heavy duty vehicles will have to be 15% lower, compared to 2019. This target is mandatory and can be achieved using technologies that are already available on the market.

In 2030, emissions have to be at least 30% lower. This target is aspirational, giving long-term direction. It will be reviewed in 2022 to incorporate additional information on the new technologies needed to meet this target.

As a first step, the CO2 emission standards are proposed for large lorries, which account for 65% to 70% of all CO2 emissions from heavy-duty vehicles.

In 2022, the scope will be extended to include other vehicle types such as smaller lorries, buses, coaches and trailers.

Incentives. The Commission proposes to support these technologies and foster innovation through an incentive system which complements the Action Plan on batteries. This system of super credits will reward those manufacturers who will invest more in innovative technologies, while preserving the environmental integrity of the CO_2 targets. It also includes zero-emission buses which are needed for cleaner air in cities.

Monitoring and reporting of CO_2 emissions from lorries. The following measures enable the implementation of the proposed emission standards:

- Certification Regulation on the determination of the CO2 emissions and fuel consumption of new lorries
- Proposed Regulation on monitoring and reporting

The monitoring and reporting Regulation provisionally agreed by the Council and the European Parliament will require that, as of 1 January 2019, lorry manufacturers monitor and report annually to the Commission the CO2 emissions and fuel consumption of each new vehicle above 7,5 tonnes they produce for the EU market.

From 2022 these measures will be extended also to smaller vehicles.

This information will be calculated using the new Vehicle Energy Consumption Calculation Tool (VECTO), in application of the certification Regulation.

It is worth to notice that all the collected data on CO2 emissions and fuel consumption together with other relevant technical information of the vehicles, including the aerodynamic drag, will be made publicly available by the European Environment Agency on behalf of the Commission, starting in 2020 to cover data monitored in 2019 [21].

Vehicle Energy Consumption Calculation Tool (VECTO). The information required for monitoring and reporting will have to be calculated using the Vehicle Energy Consumption Calculation Tool (VECTO), a simulation software that measures the CO_2 emissions and fuel consumption of high duty vehicles for specific loads, fuels and mission profiles (e.g. long haul, regional delivery, urban delivery, etc.), on the basis of input data from relevant vehicle components.
VECTO has been developed by the Commission in close cooperation with stakeholders.

2.4 Conclusions

All the technologies presented, especially the electric as confirmed by the new full-electric trucks recently launched on the markets, are evolving.

On one side, the ICE is not dead. As confirmed by the ICCT study, it will still represent more than an option for the manufacturers, thanks to the minimum foreseen 20% CO2 saving in 2021.

On the other side, EVs are growing at an impressive pace. From a technological point of view, Solid State or Li-Magnesium batteries promise to further increase energy density and lifetime while reducing weight. Moreover, thanks to the economies of scaleenhanced by passenger cars, price of batteries is expected to decrease in the next years. These aspects will be further analyzed in Chapter 4.
Regarding infrastructures, companies like ABB are already testing new generation recharging points featuring a power of 350 kW. They will then allow to fully recharge the batteries of trucks in few hours.
In a close future we will probably have electric trucks with lower price, larger range and shorter recharge time

Lastly, HEVs represent an interesting technology for their capacity of combining benefits of conventional and electric engine. Anyway, the increased cost, complexity and weight may be an obstacle for their diffusion.

In the short term, while electric trucks look like a perfect fit for urban missions, they will probably suffer from range limitation on longer distances, in regional and long-haul applications. For this reason, ICE trucks will probably continue to be the first pick for such missions.

In the medium-long term, thanks to the technological advancements of the batteries, the situation might change. By means of a greater range, they will be suitable to cover also regional, and, in the long term, long-haul missions. Please note that the diffusion for long-haul applications will strictly depend on the availability of recharging infrastructures, that in some European countries is still very low.

3. Fleet Electrification: Technologies, Infrastructures and Logistic Models

3.1 Technological Enabling Factors

Nowadays, freight transport produces 24% of the transport emissions in Europe. Furthermore, as we will see in detail later one, freight transport volume is expected to grow in the next years, due mainly to the new commerce trends. It results clear that, considering that the actual fleet is mostly composed by diesel vehicles, new technologies to lower emissions are needed.

In this landscape, truck electrification constitutes one of the most interesting outlook. Anyway, the electrification of heavy vehicles is evaluated to be much harder of passenger vehicles, even if still possible.

Let us give a look to the main technological factors that affect the electrification potential of the heavy-duty fleet.

3.1.1 Battery Energy Density

Nowadays, the main obstacles to the diffusion of electric vehicles are two: range and price. From a technological point of view, the battery is the component that most influences these two factors. It is then interesting to understand what has been the evolution of these two parameters and what the future scenario will look like.

The specific energy of batteries – that is, their capacity of storing energy per kilogram of weight – is still only 1 percent of the specific energy of gasoline. Battery cells today can reach nominal gravimetric densities of 140 to 170 watt-hours per kilogram (Wh/kg), compared to 13.000 Wh/kg for gasoline. Anyway, not all the available volume for batteries can be filled in with cells. It follows that the specific energy of the resulting battery pack is typically 30 to 40 percent lower, or 80 to 120 Wh/kg. Even if that energy density were to double in the next ten years, battery packs would still store only some 200 Wh/kg of weight.

3.1.2 Cost Evolution

Batteries are the main reason why EVs are more expensive than conventional ones. By the way, this situation is not expected to be long lasting: in fact, the cost of the batteries is in a sharp decreasing trend, making expectable a consequent reduction of electric vehicles price in the very next years.
Three are the major drivers for batteries cost reduction:

- Technological improvements
- Economies of scale
- Competition among manufacturers

Bloomberg New Energy Finance (BNEF) conducted a 7-years-long survey to track the cost evolution of lithium-ion batteries from 2010 to 2016 [22]. The results are showed in Figure 13.

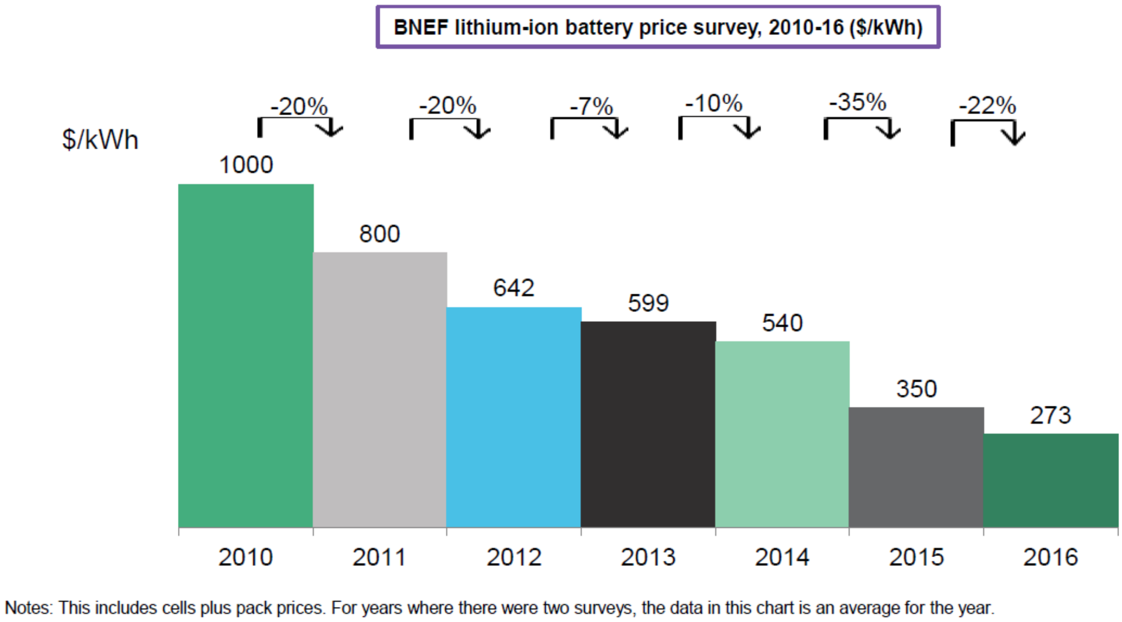


Figure 13: battery price survey result 2010-2016. Source: BNEF.

Prices dropped by almost 75% throughout the defined period. Altough it is already an impressive outcome, prices will most likely continue to drop in the next years, as showed by the BNEF forecast below.

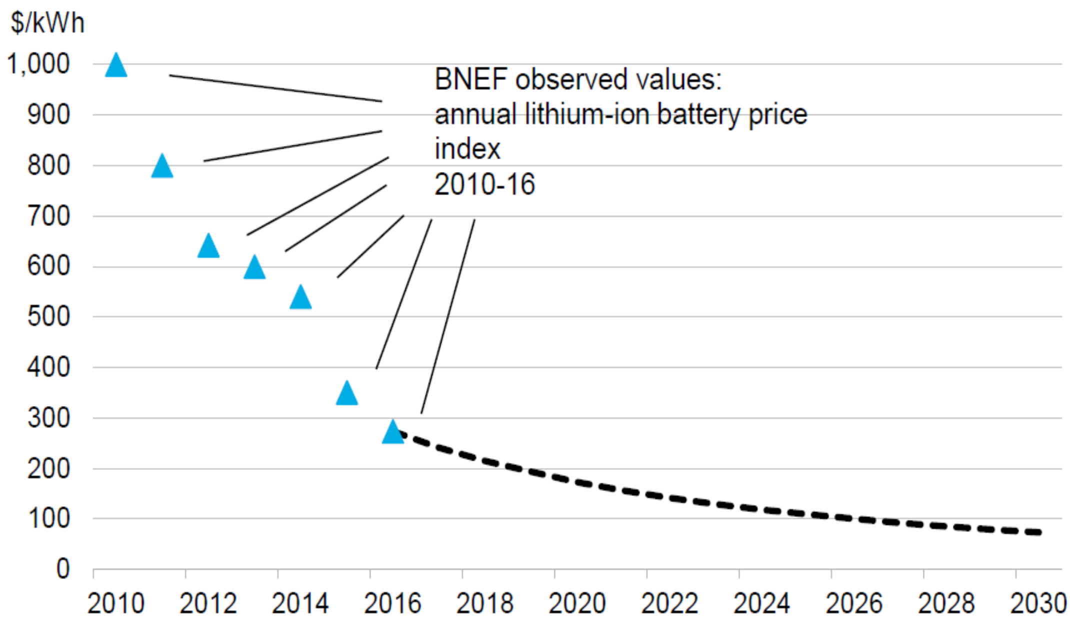


Figure 14: battery price trend 2010-2030. Source: BNEF.

In 2026 the price of batteries is expected to go below 100 $/kWh (-50% vs 2019).

As already underlined, batteries are the most expensive component of an EV. This means that a reduction in price of the batteries will heavily influence the price of the final vehicle, as shown in Figure 15. Please notice that the data presented are for passenger cars; anyway, the trend is expected to be similar for HDVs.

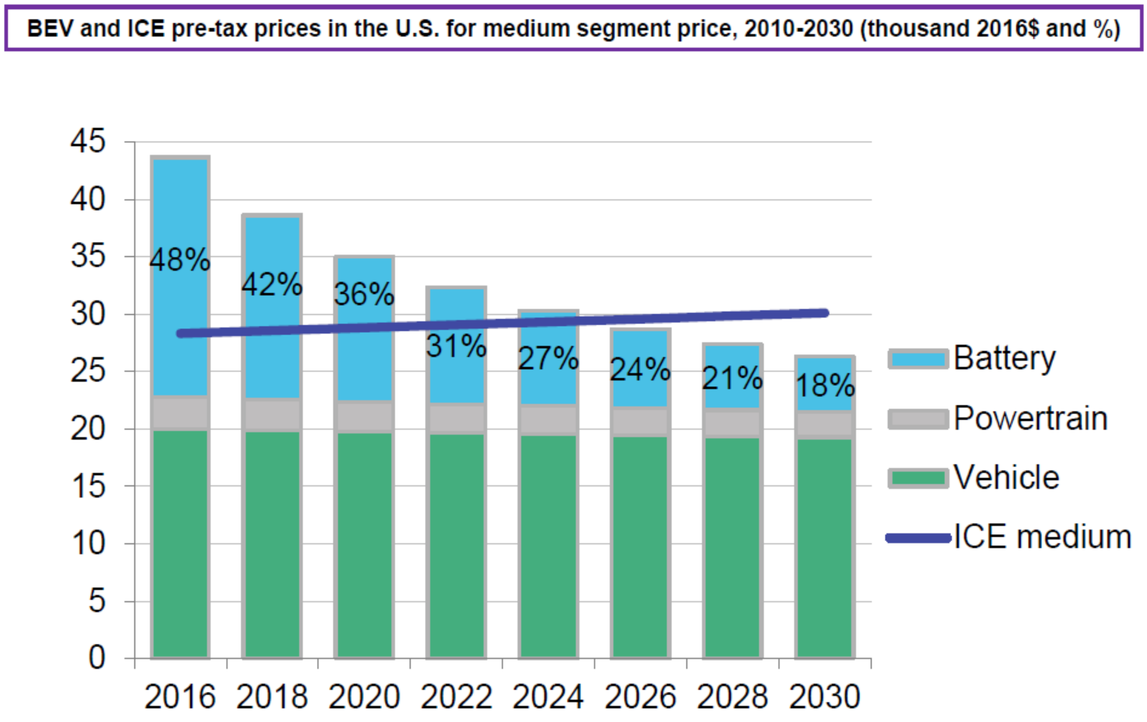


Figure 15: expected price trend for electric passenger cars in the period 2016-2030. Source: BNEF.

It is worth to notice that ICE vehicles` price is expected to slightly grow against the price of EVs, which will drop by around 30% until 2030.

Resuming, we can easily expect EVs (passenger cars and HDVs as well) to be significantly cheaper in the next future.

3.2 Infrastructures and Logistic Models

3.2.1 Energy Replenishment

As more and more EVs are entering the market, there is a rising demand for public recharging stations. Nowadays, when the EV's batteries are depleted there are two possibilities: recharge them or exchange them (battery swapping). Charging stations can be divided into two categories: fast charging and slow charging. A fast refueling station can quickly recharge an EV in less than twenty minutes (passenger car), but this kind of charging can significantly shorten the life of the batteries. Conversely, a slow refueling station needs a longer time to recharge an EV. With slow recharging stations of Level 1 or 2 (110–240 V), vehicles need to wait from 2 to 8 hours to fully charge their batteries. At recharge stations of Level 3 (480 V), charging a battery fully takes about 20–40 min.

It is clear that recharge time has been a critical factor influencing public acceptance of EVs. A major solution is represented by the “Battery Swap”. It consists in removing the existing battery that is nearly depleted and replace it with a fully charged one. The main benefit associated with the swapping model is the speed. The whole operation could take less than ten minutes, which is comparable with conventional vehicles and much faster than most of the current recharging stations. Further benefits of battery swap are the following:

- the charging of depleted batteries can be performed in the night when the charging cost is low;
- the provision of grid-support service in a centralized charging and discharging manner;
- the ability for drivers to resume their journeys in few minutes with a full-capacity battery;
- the charging of batteries in slow-charging mode to extend their lifetime; and

A battery swapping model could be considered more appropriate than a battery recharging model since the former not only improves the productivity of vehicles but also lowers the charging cost. Due to the battery driving range limitation and the nature of battery swapping, distribution network optimization with a battery swapping infrastructure could be an important part of establishing any green Logistic & Transportation policy. However, companies can take this possibility, since the best battery swapping infrastructure ownership model is the company-owned business model, which indicates that the L&T companies establish and operate the battery swap stations for the EVs by themselves. This way, determining the ideal battery swap stations location strategy and vehicle routing plan for a distribution network is mainly a question of service level and operational cost for the logistics enterprises [23].

The major challenge for battery swapping is represented by the lack of standardization of the batteries. As far as the batteries will not be exchangeable, the battery swapping will be something hard to realize. That is why the majority of papers in the literature tackle transportation problems using EVs with charging stations. Nevertheless, there is an emerging number of works considering battery swap stations.

3.2.2 Recharging Stations location

As mentioned before, one of the main issues to be addressed regarding the EVs success is to determine the location of recharging stations. To do this, specific methods that allow to minimize the costs of developing an alternative infrastructure are employed.
Indeed this “station location problem” can be considered a specific case of Facility Location Problem (FLP). The key questions commonly faced by facility planners include:

- the number of facilities;
- the locations of these facilities;
- the types of facilities (in terms of size, product variety and other design aspects).

Most location models focus on either minimizing the average cost of travel (the median problem) or minimizing the maximum cost of travel (the center problem) [23].
A further analysis of this models will not be performed for reasons of brevity.

3.2.3 Capacity of Recharging Stations

The size or capacity of recharging stations for EVs affects the transportation planning. In fact, the capacity of these stations is limited and during a specified time window a station cannot serve more than its capacity, especially when speaking about recharging stations. This means that only a small number of vehicles can be recharged simultaneously. Changing the departure times of vehicles belonging to a logistic company may require different times for recharging. Moreover, travelers who start their trips in different times may also reach a station at different times. If the station is occupied, the vehicles must wait in queues. The recharge time, capacity of stations, and waiting time are real problems that have often been neglected in the EVs station location literature. Hosseini and MirHassani`s [24] is one of the few works in the literature that considers some of these issues. In their work they designed a strategic plan in order to build recharging stations in such a way to minimize total costs. These total costs include stations-construction cost, waiting time cost, and refueling cost.
In the specific case of battery swapping stations, when a vehicle arrives, it requests a fully charged battery pallet to replace its nearly depleted batteries. The request could either be satisfied by a fully charged battery pallet from the station storage, or by a pallet that is just completing its charging. If the request is indeed satisfied, the vehicle in turn deposits a fully or partially spent pallet. If there are idle battery pallet chargers at the station, the spent battery pallet is placed on one of them and its recharging begins, otherwise it is kept in a queue until a battery pallet charger is available. If, instead, there is no fully charged battery available at the station, then the vehicle should leave and go to a different station or it could wait for a battery to fully charge, which may take some time. The vehicle could even take, if necessary, a replacement battery that is only partially charged and use it to travel to another battery swap station on its route. In this case, the vehicle will have to stop earlier than planned, and this influences the routes planning, because the vehicle is forced to perform additional not covered stops.
Depending on both the number of battery pallet chargers the station holds and number of battery pallets the station keeps on hand, the size and attendant cost of the station will change. The availability of charged battery pallets at any given time depends on the size of the station, the inventory of pallets, and the demand for charged pallets the station is experiencing. The station incurs an indirect cost from the unavailability of charged pallets when an EV arrives for an exchange because the driver will not have to pay for a battery swap, and there may be a loss of goodwill from the unserved customer. Models to evaluate total direct and indirect costs for possible decisions on station sizing and inventory holding would be very important in designing the battery swapping infrastructure [23].

Zheng et al. [25] proposed a method for locating and sizing battery swap stations in distribution systems, which may be two determinants keys in the take-up of EVs. The problem is modeled as maximizing the net present value of the battery swap station project, where the battery swap station model, load type, network reinforcement, and reliability are taken into consideration.

3.2.4 Impact on the Electric Grid

3.2.4.1 Electric Mobility: a Challenge for the Power Sector

While the adoption of EVs can provide new opportunities – such as creating additional electricity sales for utilities and a demand for charging infrastructure and related services – the charging of EVs at a large scale can be a challenge for local distribution grids and their operators, if not properly managed. A growing adoption of electric mobility coincides with other trends that put higher requirements on the grid and power system, such as the increasing share of renewables and distributed generation, as well as demands for increasing energy efficiency [26]. These trends, with the related grid functionality requirements, will drive the transition from

traditional to smarter grids.
The challenge posed by the increasing use of electricity by EVs lies not so much in the volume of the associated power demand, but rather in the potential increase in peak demand, which is determined by the speed, moment, and location of EV charging. In general, a growing number of EVs will cause a higher demand for electricity. Considering the case of Netherlands, driving an EV 15,000 km per year and charging it solely at home would roughly double the household's electricity demand, taking it from about 3,500 kWh to about 6,500 kWh per year. Despite this marked volume increase at the household level, significant EV penetration would only lead to a moderate rise in total demand – estimates suggest that even if EVs comprised 20% of all cars on the road in Europe by 2020, associated incremental electricity demand would be 3-4% of base case without large-scale EV adoption. It follows that, from a volume perspective, this additional electricity demand could be accommodated by the power sector without additional significant investments.
More concerning would be the potential increase in peak demand caused by the charging of EVs. With the diffusion of fast-charging, high demands for short periods are produced. The moment of charging also impacts the grid. Throughout the day, electricity demand follows a load curve; when EV drivers charge their cars can either intensify peaks or level them out. Finally, where the charging takes place can also affect the power infrastructure.
Over time, the growth of EVs share can lead to a significant increase in the stress put on distribution grids, depending on whether the charging is unconstrained or controlled. Unrestrained EV charging at home can significantly increase residential peaks, especially since charging when returning home would increase the common "afternoon peak" in household electricity consumption. The combined impact of several such residential peaks on the distribution grid would be particularly high in neighborhoods with a high penetration of EVs, and would affect lower-voltage distribution grids the most, requiring expensive grid upgrades [26].

In addition to load demand potentially caused by large-scale EV charging, renewable energy sources are impacting the power infrastructure. The share of renewable energy sources in the EU power generation mix has grown from 13% in 1990 to about 20% by 2010, and will most likely continue to increase (fortunately) towards EU's 20-20-20 targets, which features a target of 20% of renewable energy in the EU's gross final energy consumption by 2020. This increase has two distinct effects that exert stress on the grid: supply volatility and distributed generation.

- Supply volatility. The growth in renewable energies creates more intermittency and volatility in the power supply, as wind and solar energy are not consistent in terms of production over time.

- Distributed generation. Mostly due to the installation of solar photovoltaic systems (PVs) by individual homes and businesses, consumers of electricity are turning into small-scale producers. If the electricity generated by distributed generation is not consumed locally, it can flow back into the distribution grid, causing reverse flows, which the grid and metering system may not be able to accommodate.

Of the two grid-related effects of renewable energy, distributed generation is expected to have the highest impact. In Europe, the total installed capacity of solar PV systems reached 69 GW in 2012, ~80% of which is connected to low-voltage grids [26]. This solar capacity impact on the electricity infrastructure is already being felt in Europe, with several cases of "grid stress". The grid challenges in accommodating significant reverse flows from distributed generation are already apparent today (Figure 16).

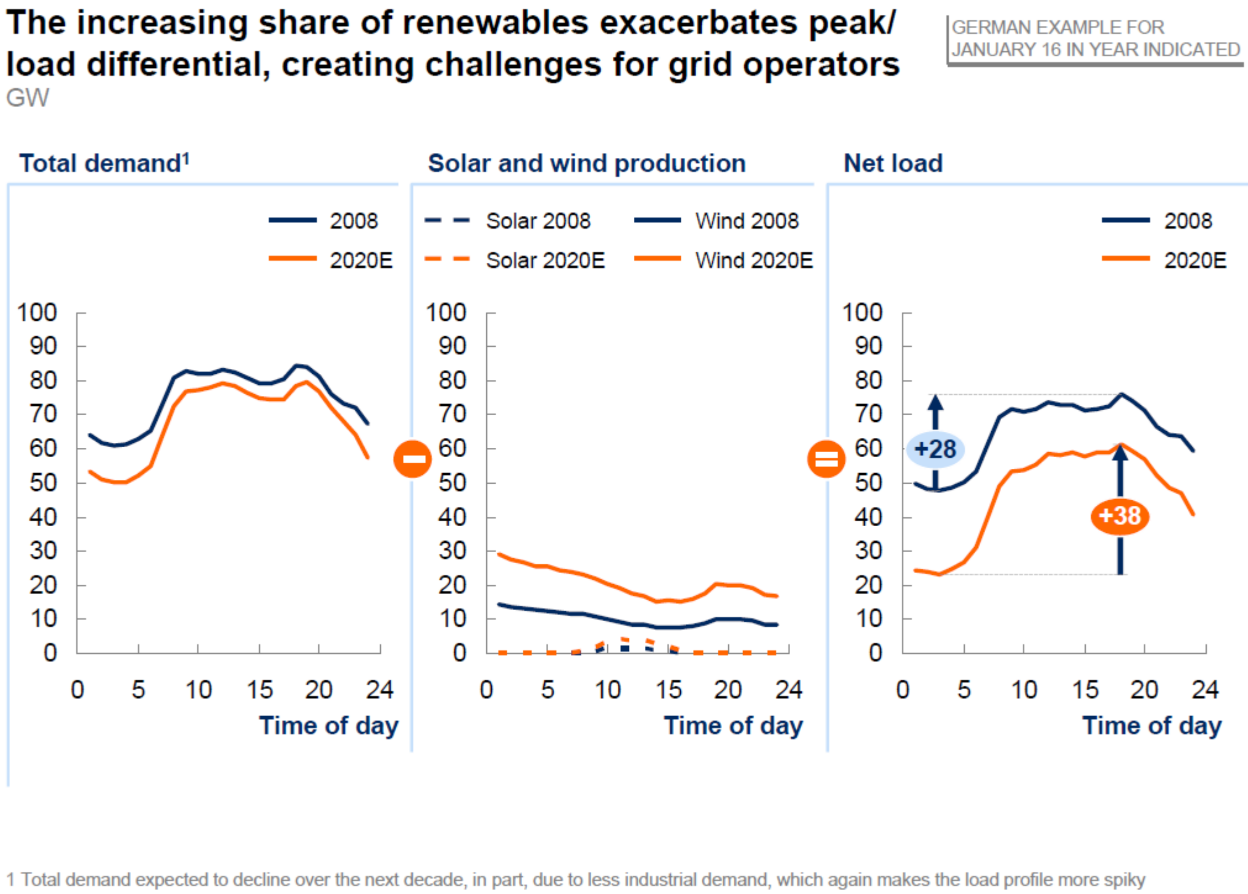


Figure 16: trends of demand and renewable production of electricity 2008-2020. Source: McKinsey.

It is fundamental to anticipate future load requirements in order to avoid costly grid upgrades in the future. Such grid upgrades would consist of replacing existing cables with thicker versions and upgrading the transformers feeding into the distribution networks. Without smart systems, investments in the grid to integrate demand from a large population of EVs will turn out to be larger than the base case without EVs and, in certain areas of high EV penetration, may be as high as double [26].

To avoid these investments, grid operators are looking for new solutions that help to balance the grid, and chief among these today are energy efficiency targets. In particular, the EU has set the target of achieving a 20% energy efficiency improvement, as part of the already mentioned 20-20-20 climate and energy goal. As part of the Energy Efficiency Directive, national governments are required to drive energy efficiency improvements in households, industries, and transport sectors. Home energy management systems can play a main role in reducing energy demand and increasing energy efficiency, since some pilots in Europe achieved energy demand reductions of 4-10%. Apart from achieving energy savings, such home energy management systems can also be used for intelligent demand-side management, which will become a critical feature in stabilizing the grid in future. Early pilots have shown that peak demand reductions of 12-20% are possible, when combined with (and reacting to) critical peak pricing tariffs [26].

3.2.4.2 EVs: from Problem to Solution

In addition to the environmental benefits from switching away from oil-based fuels, EVs are uniquely positioned to help maintain electric system stability. The promise of EVs providing energy and capacity to the grid has been discussed widely, but is yet unrealized in a large scale.
Since personal vehicles are typically utilized only a small fraction of the day, they can be made available the rest of the time for a secondary function. Grid-connected EVs can help balance the electric system by serving as a capacity and energy resource, storing energy generated during off-peak periods, and returning it to the grid during peak electricity demand periods. Their connection to the grid can also be used to increase total electric system efficiency by reducing the ratio of peak to off-peak load, a key metric of efficiency for system monitors.

Over the longer term, if EVs reach large-scale market penetration and smart grid systems become more commonplace, EVs could then become part of the solution, contributing to load-shifting and performing power supplying (V2G/V2B).

- Load-shifting. I.e., shifting demand from peak moment (e.g., working day afternoon) to lower-demand periods (e.g., night) could be accomplished by instituting controlled charging of EVs and could represent an important step in minimizing the impact or even improving management of existing peak demand for electricity, as shown in Figure 17.

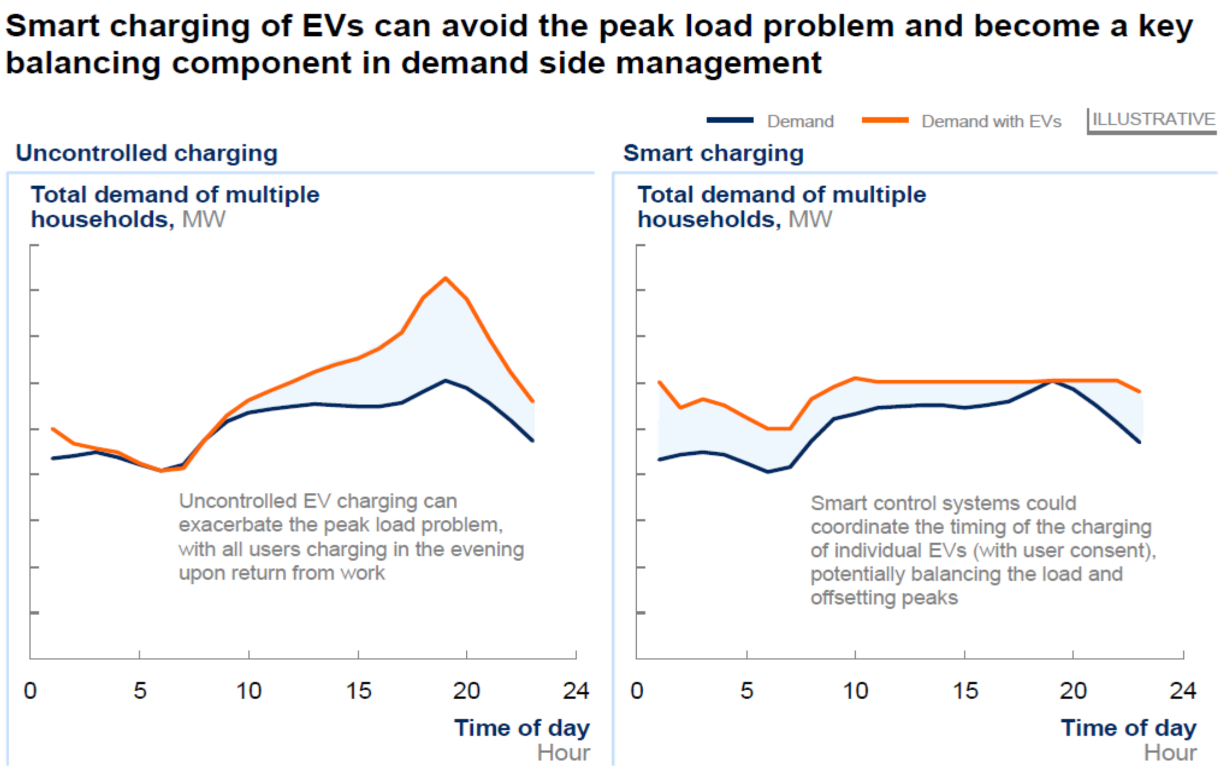


Figure 17: benefits of controlled charging on electricity demand. Source: McKinsey.

- Vehicle to Grid (V2G). Going one step further than just controlling their demand for electricity, EVs could be equipped to actually provide electricity to the grid. This functionality can be even more effective for balancing purposes and managing the electricity load. To this purpose, Volkswagen and

Lichtblick announced a pilot in Berlin employing 20 VW e-Ups that are able to charge back to the grid. In the US, a collaborative V2G pilot between BMW and the University of Delaware, employs 15 (stationary) Mini-E's coupled to the grid in which bidirectional flows are being managed.

- Vehicle to Building (V2B). The storage capacity of the batteries in EVs can also be exploited to take advantage of different electricity tariffs throughout the day, as one fully-charged BEV could theoretically power a household for one or more days depending on its battery size. For example, with typical European household demand of ~10 kWh per day, a fully-charged battery of a Nissan LEAF (40 kWh) would be able to deliver power for 4 days. Nissan is currently piloting this V2B approach in Japan, with the idea that it will allow companies to regulate their electricity bills using the batteries of the EVs of their employers. It has carried out an initial pilot at its own Advanced Technology Center in Atsugi City, Japan, using 6 Nissan LEAFs, which according to Nissan led to a 2.5% reduction of electrical power use during peak hours, yielding electricity cost savings.

Further, the decrease in Li-ion battery prices has led to growing interest in using automotive battery technology (or even second-hand EV batteries) as local stationary electricity storage solutions, for households, buildings, or grid nodes – providing a potential solution for storage for distributed renewable generation [26].

4. Impact assessment of HGV Electrification in Urban Logistics

4.1 Objectives

The aim of the work is to determine the EVs impact in terms of CO_2 reduction in heavy urban operations. In addition also the quantity and quality of recharging stations needed as well as the impact of the electrification on the national electric grid will be analysed.

4.2 Methodology

For this objective a computational model has been developed, which allows to calculate the consumption of the electric versions of the trucks and to compare them with the consumption of the corresponding diesel versions of the trucks.

4.2.1 Missions

To estimate the potential benefits of fleet electrification in urban logistics, three typical missions have been chosen and analysed: Multi Drop Delivery, Local Distribution, Garbage Collection.

Multi Drop Delivery (MDD)

It is a mission characterized by a high number of start and stops, low average speed and low daily mileage. It is typical of courier deliveries.

Local Distribution (LD)

Very similar to the Multi Drop Delivery, it features less start and stops and higher distance between stops. Consequently, the average speed and the daily mileage result higher. It is typical of retail freight distribution (supermarkets, shops, ..)

Garbage Collection (GC)

It is a mission characterized by three key areas:

- the Depot, from which the vehicle will depart;
- the urban Collection Area, in which the vehicle will collect the garbage;
- the Landfill, in which the vehicle will drop and deposit the garbage collected.

For the first two missions the logistic models adopted foresee a Consolidation Center located out of urban area and a constellation of customers to be served by vehicles located in the vertex of a sort of “Manhattan road network” with a predefined length of the edge of the mesh (distance between customers which is a parameter of the mission)

The following picture shows the model:

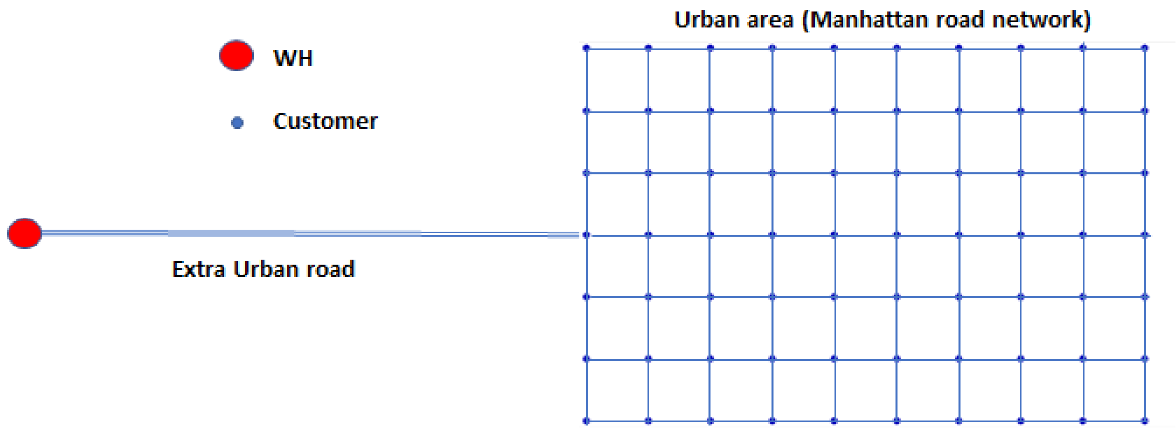


Figure 18: Manhattan road network model

With this simplification the mission is composed by a trip (mainly in extraurban context) between WH and urban area and a tour for urban distribution.

Using the “Manhattan road network” having customer on each vertex of the mesh, we are sure that an optimal tour (Hamiltonian cycle at minimum cost) exist and its length is easy to compute without solving explicitly the TSP. In fact the length (or duration) of optimal tour will be the results of the product of number of customer and length (duration) of edge between 2 adjacent customer.

The picture below shows the solution of TSP for a Manhattan road network with 70 customers (TSP solver Concord Tool)

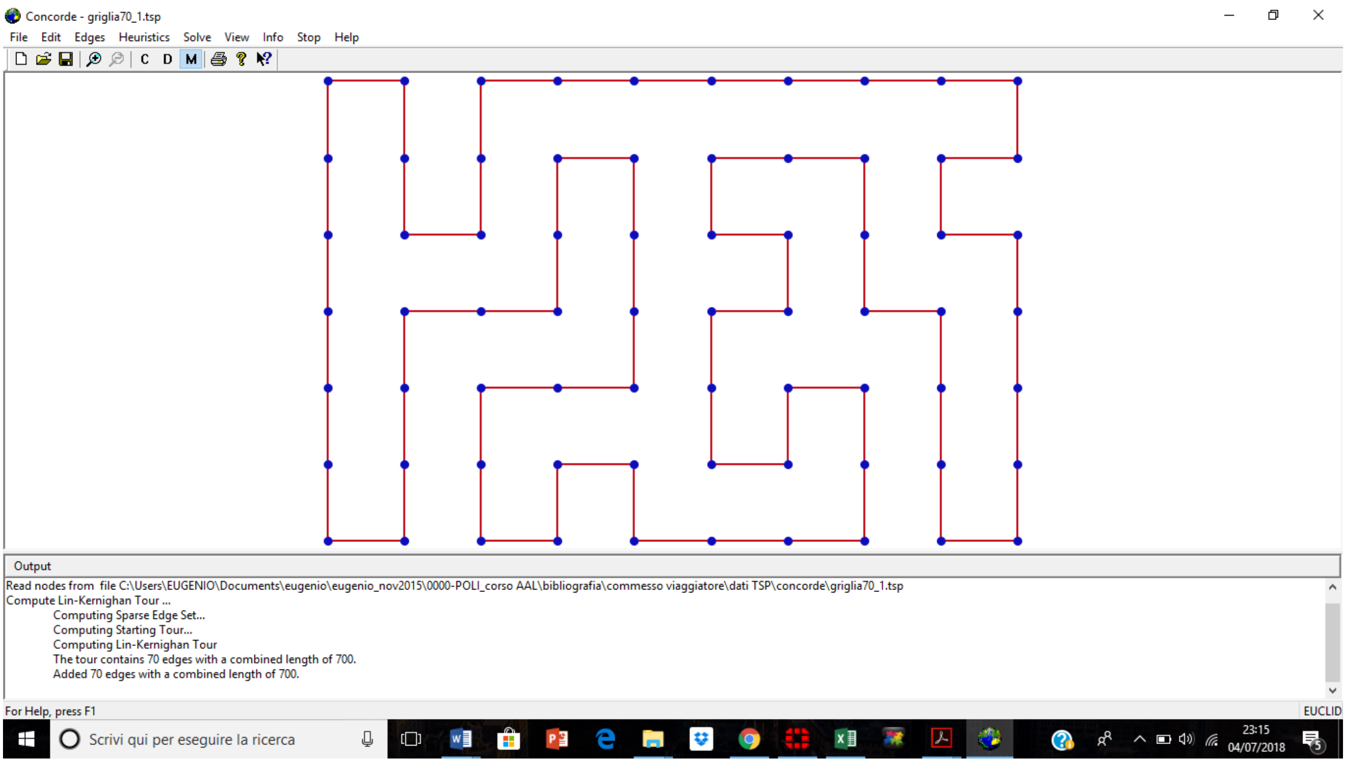


Figure 19: TSP solution for a Manhattan road network with 70 customers

For the third mission (Garbage Collection) the scheme of logistic model is depicted in the following picture.

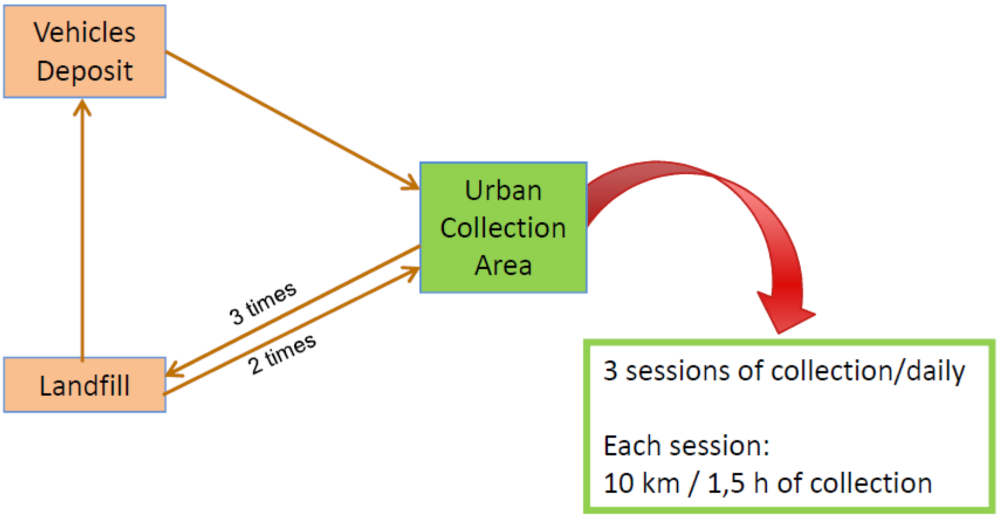


Figure 20: scheme of Garbage Collection mission. Source: IVECO.

Also in this case the urban Collection Area is sketched as “Manhattan road network”.

4.2.2 Vehicles

The vehicles employed for such missions are the IVECO Eurocargo and the IVECO Stralis: the first being employed for the two distribution missions, the second for the Garbage Collection.

IVECO Eurocargo

Figure 21: IVECO Eurocargo. Source: IVECO.

Main Features:

- Engine: ICE and EV
- Length: AROUND 10 meters
- Weight: 18 ton
- Wheelbase: 5700 mm
- Traction: 4x2 - 18 ton
- Suspensions: Pneumatic

IVECO Stralis

Figure 22: IVECO Stralis. Source: IVECO.

Main Features:

- Engine: ICE and EV
- Length: AROUND 10 meters
- Weight: 26 ton
- Wheelbase: 4200 mm
- Traction: 6x2
- Suspensions: Full Pneumatic
- Steering rear axle

4.2.3 Scenarios

Even with the simplified logistic models that we have described in previous paragraph, the scenarios for assessment must be realistic.

To do that we have selected Turin as reference city for the assessment.

For multidrop and local distribution mission we have to derive scenario data from the case of Milano that in 2003 conducted a very detailed study made by the Politecnico di Milano on freight transport in the city, so it has been possible to derive some realistic figures for the scenario definition.

In the cited study the metropolitan area of Milan was subdivided in three concentric area (Figure 23):

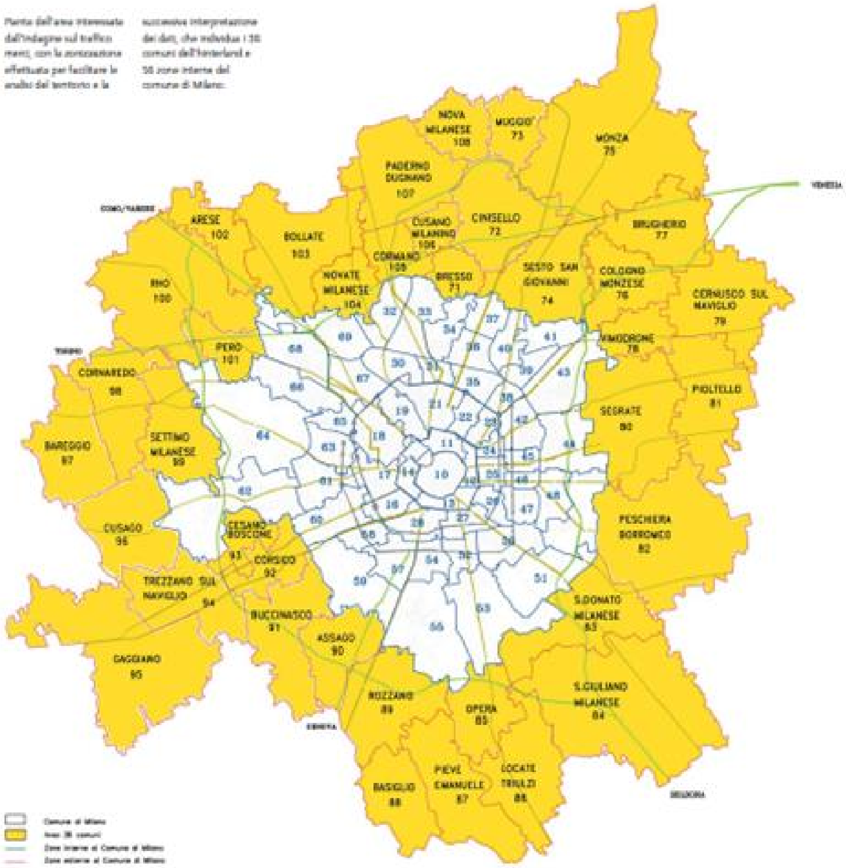


Figure 23: areas of Milan metropolitan area.

On each boundary between the areas all the relevant roads have been equipped with traffic sensors (with count&classify functionality) and interviews to a sample of drivers have been conducted to know habit and qualitative information.

In the following table the relevant results of flow of Freight vehicles entering Milano (first two column) are shown. The estimate of vehicle with GVW=18t has been done using data coming from “Albo Autotrasporto”, that know the fleet composition for each logistic company registered in the “Albo”.

	tot vehicle (7 -21)	comm Vehicle >3,5t		comm vehicle 18t (*)	
ingressi da barriere autostradali	55300	30415	55%	11862	39%
ingressi da cordone esterno	31400	12175	39%	4748	39%
ingresso da cordone interno	18000	2220	12%	866	39%

Table 11: freight vehicles flow of Milan.

For the assessment we consider the flow entering the “cordone Interno” (866 vehicles from 7 to 21). Just to move to a Turin scenario we consider the value of Milano corrected with a coefficient which is the ratio of the populations (70%). The total fleet in Turin for serving the urban area is estimated in 606 vehicles. This will be splitted in MDD vehicle (46%) and LD vehicle (46%).

For garbage collection mission the scenarios come from Turin where some data on garbage collection operations are available from the “carta dei servizi” of the local Company.

The logistic model for Garbage Collection mission is shown in the following picture:

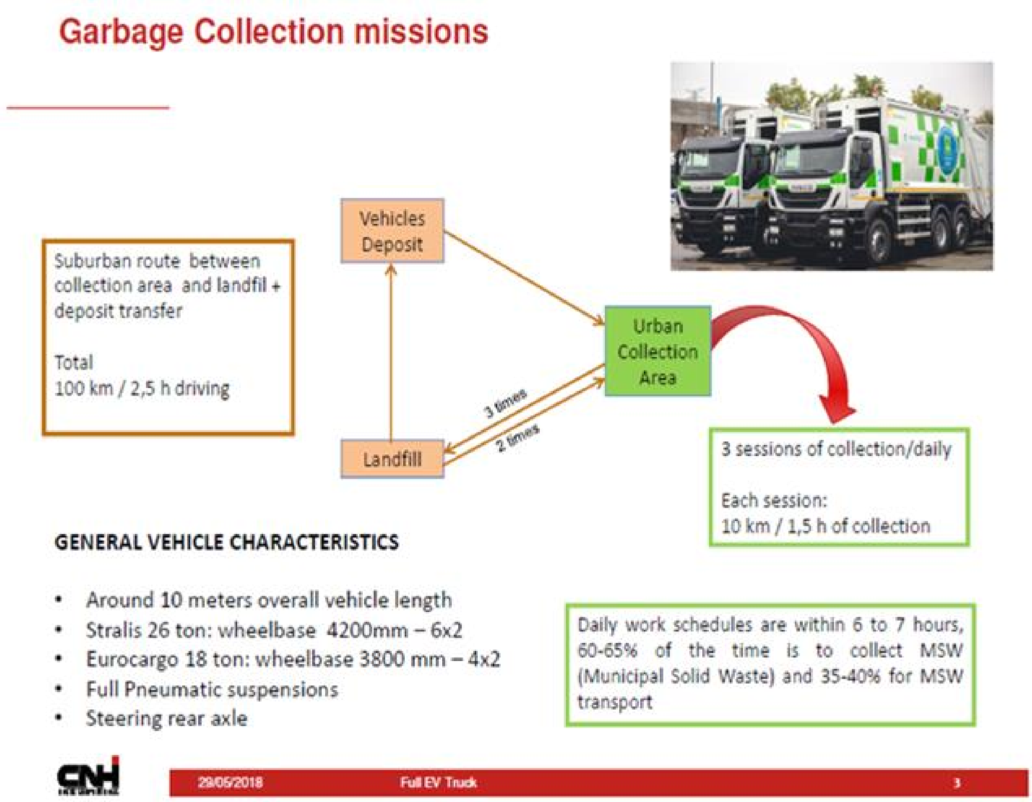


Figure 23: scheme of Garbage Collection mission. Source: IVECO.

The idea for sizing the scenario is to start from the number of bins used by the city (30769) and place them at the vertex of a grid with square mesh covering the entire surface of the city (approximated with a square).

In the case of Turin, the surface of the city is 130 square kilometers, so the square that approximates the urban area has the side of $130^{0.5}$ = 11.4 km. The 30769 bins can be placed in a grid with square mesh with $30769^{0.5}$ = 175 bins placed on the side, which are then distributed over 11.4 km , which means an interdistance of 65 m. If we consider that bins are often grouped in each location and we suppose that groups are made with 2 bins, we have half of the locations (15384 bins location) that means an interdistance between location of 92 m. For the scenario assessment we consider the more dense situation with interdistance of 65 m.

To find a correct dimension for the fleet used for Garbage collection require some elaboration which are summarised in the Table 12.

Starting from distance travelled for transfer and collection, time allocated for operations and interdistance between bins, the frequency of collection is computed. Knowing that, the total number of operation per vehicle and the number of vehicle needed can be computed.

INPUT	km	hrs
Daily work	130	7
Collection	30	4,5
Transport	100	2,5
OUTPUT		
total trip Transport	7	
single trip lenght	14,29	km
lenght full load	42,86	km
lenght empty	57,14	km
speed transport	40,00	km/h
time for collection session	1,5	h
distance between collection point	0,065	km
time for collection operation	60,00	sec
speed collection phase	15,0	km/h
time for cycle (move&collect)	0,021	h
frequency	47,6	op/h
commercial speed	3,1	km/h
distance in one session	4,6	km
number of operation in one session	71,4	
number of operation for collection (1vehicle)	214,3	
number of bins (operation)	30769	
number of vehicle	144	

Table 12: Garbage Collection fleet dimensioning.

Last elements of the scenario relevant for the assessment are:

- the total amount of emission of CO_2 in Turin. From the annual report of “Provincia di Torino” dealing with Energy and emission we see that total emission account for 14500 Ktons/year (Year 2007).
- the total amount of electric energy consumption in Turin. From the annual report of “TERNA” dealing with electric energy production and consumption we see that total consumption account for 10054 Gwh/year (Year 2016).

4.2.4 Model Inputs

In the following paragraph the inputs for the computational model are described. There are two types of input:

- Mission Inputs
- Vehicle Inputs.

4.2.4.1 Mission Inputs

Mission inputs consist in duration of the mission (time of work for the vehicles), speed for urban and extraurban road (considered as speed including only the traffic stops, without the service stops), number of stops per hour and average stop duration. Since the service stops are made only in the urban environment, the extra urban travelled distance was also given.

4.2.4.2 Vehicle Inputs

Vehicle inputs are given for both versions (ICE/EV) of both trucks (Eurocargo/Stralis). Load components and unitary fuel consumption are given for each of the four combinations of vehicle-version. Additionally, for the EV versions of both the trucks are given the available space for the battery pack and the volumetric and gravimetric densities of current state-of-the-art batteries: they will allow to estimate the overall dimension of the battery pack and the corresponding energy that it is possible to store inside it, as well as the resulting weight.

The unitary fuel consumptions of ICE vehicles have been computed with COPERT model, while the unitary energy consumptions of the electric trucks have been computed using a simple dynamic model of the vehicle considering just all the resistant forces and computing the power and energy needed for moving with a predefined speed.

For the calculation of consumption and CO_2 emissions of ICE Vehicle, but also of the other major pollutants (NOx, PM, CO, HC), it is available an authoritative source: European Environment Agency (EEA) which, in 2012, published a revision of the "EEA - Guidebook-2009", which for the vehicles covered provides, in terms of average values relating to the "fleet" of vehicles in circulation, consumption and emission according to speed, load and slope.

Consumption and emissions are obtained on a statistical basis, referring to a mix of simulations (PHEM model), bench tests on standard cycles and road tests with real journeys. These are therefore "average" value.

COPERT is a methodology and a database (prepared by EMISIA) that provides fuel consumption and emissions of all pollutants (CO, CH, NOx, PM) for all categories of vehicles.

Commercial vehicles are identified by the GVW Gross Vehicle weight, (14 class of GVW)

Tipo veicolo
Articulated 14 - 20 t
Articulated 20 - 28 t
Articulated 28 - 34 t
Articulated 34 - 40 t
Articulated 40 - 50 t
Articulated 50 - 60 t
Rigid <=7,5 t
Rigid >32 t
Rigid 12 - 14 t
Rigid 14 - 20 t
Rigid 20 - 26 t
Rigid 26 - 28 t
Rigid 28 - 32 t
Rigid 7,5 - 12 t

Table 13: COPERT vehicle weight category selection.

and by the class EURO (8 EURO labels).

cat euro	TEC name
80ties	Conventional
Euro-I	HD Euro I - 91/542/EEC Stage I
Euro-II	HD Euro II - 91/542/EEC Stage II
Euro-III	HD Euro III - 2000 Standards
Euro-IV EGR	HD Euro IV - 2005 Standards
Euro-V EGR	HD Euro V - 2008 Standards
Euro-V SCR	HD Euro V - 2008 Standards
Euro-VI	HD Euro VI

Table 14: COPERT EURO category selection.

The data in the database are also depending on 7 class of slope of the road:

-6%
-4%
-2%
0%
2%
4%
6%

Table 15: COPERT slope selection.

and of the 3 class of load percentage:

0
50
100

Table 16: COPERT load selection.

An example of the COPERT function for FC (in l/100km) is shown in the following picture

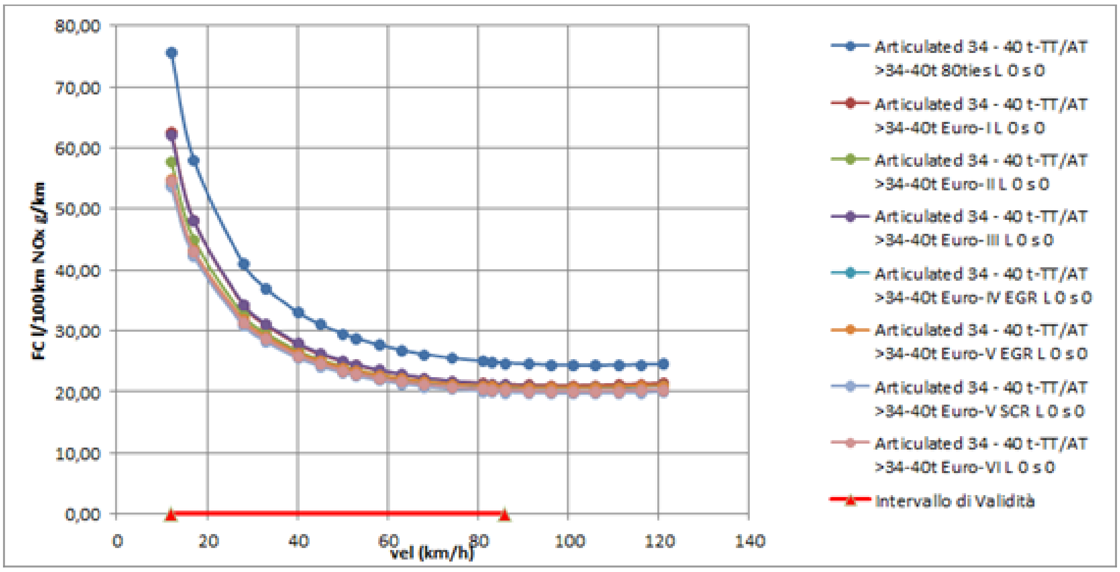


Figure 24: ICE consumption function.

As it is evident FC is very high for slow speed and reach minimum for speed around 80 km/h with a slow increase for higher speed.

For EV energy consumption the dynamic model before mentioned has been used. In the following picture the energy consumption per Km and per ton transported is shown.

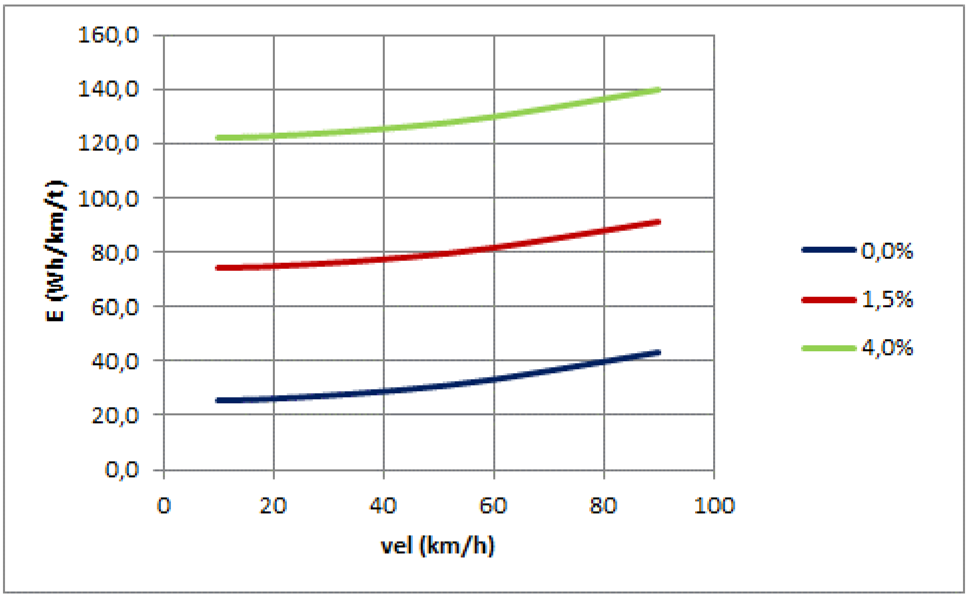


Figure 25: EV consumption function.

Since the function are quite “flat” the value of energy consumption of 80 Wh/km/t has been used into the model for all the value of speed.

Below are summarized the inputs of each category.

Category				Parameters	Missions		
					Multi Drop Delivery	Local Distribution	Garbage Collection
Mission				Duration [h]	8	8	7
				Urban Speed [km/h]	15	30	15
				Extra Urban Speed [km/h]	50	70	40
				Stop Frequency [1/h]	30	15	48
				Stop Duration [min]	1.2	1.6	1
				Extra Urban Distance [km]	60	60	100
				Average Load Factor [%]	40	40	40
				Fleet Dimension [n vehicles]	279	279	144
Vehicle	IVECO Eurocargo	ICE	Loads	Ptt [t]	18		
				Body + Driver weight [t]	4,508		
				Powertrain weight [t]	0,786		
				Fuel & AdBlue weight [t]	0,266		
				Available Load [t]	12,44		
			Consumption	Urban Specific Fuel Consumption [l/100 km]	38,3	25,6	
				Extra Urban Specific Fuel Consumption [l/100km]	20,2	20,2	
		EV	Battery Pack	Volumetric Density [Wh/m^3]	150		
				Gravimetric Density [Wh/kg]	150		
				Available X [m]	2,7		
				Available Y [m]	1,2		
				Available Z [m]	0,5		
				Available Volume [m^3]	1,62		
				Available Energy [kWh]	206,55		
			Loads	Ptt [t]	18		
				Body + Driver weight [t]	4,508		
				Powertrain weight [t]	0,52		
				Max Battery weight [t]	1,62		
				Available Load [t]	11,352		
			Consumption	Unitary Energy Consumption [Wh/km/t]	80		
	IVECO Stralis	ICE	Loads	Ptt [t]			26
				Body + Driver weight [t]			5,95
				Powertrain weight [t]			1,083
				Fuel & AdBlue weight [t]			0,297
				Available Load [t]			18,67
			Consumption	Urban Specific Fuel Consumption [l/100 km]			49,5
				Extra Urban Specific Fuel Consumption [l/100km]			27,6
		EV	Battery Pack	Volumetric Density [Wh/m^3]			150
				Gravimetric Density [Wh/kg]			150
				Available X [m]			1,9
				Available Y [m]			1,2
				Available Z [m]			0,5
				Available Volume [m^3]			1,14
				Available Energy [kWh]			145,35
			Loads	Ptt [t]			26
				Body + Driver weight [t]			5,95
				Powertrain weight [t]			0,52
				Max Battery weight [t]			0,97
				Available Load [t]			18,56
			Consumption	Unitary Energy Consumption [Wh/km/t]			80

Table 17: model inputs.

4.3 The Model

In order to perform the assessment of impact of electrification of HGV vehicle in urban logistic a simple model has been built. Th model allows to sizing the battery pack for an EV once the daily mission is detailed. The model allows also to size the charging system (number of charging stations) once the dimension of the fleet is defined. The hypothesis is that charging stations are "private" and located in the premises of logistic operator.

In the following paragraphs all the equations and relations of the model are described

4.3.1 Mission Calculations

Considering the number of stops per hour, the duration of one cycle (1 transport + 1 stop) is.

$$Cycle\ Time\ [min] = \frac{60}{Number\ of\ Stops\ [\frac{1}{h}]}$$

Then the time of one travel between stops is:

$$Travel\ Duration\ [min] = Cycle\ Time\ [min] - Stop\ Duration\ [min]$$

The unitary distance between two stops is:

$$Stops\ Interdistance\ [km] = \frac{Average\ Speed\ \left[\frac{km}{h}\right] \times Transport\ time\ [min]}{60}$$

Then, considering the extra urban distance and the extra urban speed, the time spent for covering the extra urban distance is:.

$$Time\ Extra\ Urban\ [h] = \frac{Extra\ Urban\ Distance\ [km]}{Extra\ Urban\ Speed\ [\frac{km}{h}]}$$

So it was easy to calculate the time urban:

$$Time\ Urban\ [h] = Mission\ Duration\ [h] - Time\ Extra\ Urban\ [h] - \text{Time stops [h]}$$

Finally, considering the urban time, the urban distance covered during the mission is:

$$Urban\ Distance\ [km] = \left(Number\ of\ Stops\ \left[\frac{1}{h}\right] x\ Time\ Urban\ [h] - 1\right) x\ Stops\ Interdistance\ [km]$$

4.3.2 Vehicle Calculations

Starting from the max admissible weight, and subtracting all the weight components, the maximum available load for freight is.

$$Max\ Av.Load\ [t] = Max\ Weight\ [t] - (Powertrain\ Weight\ [t] + Body\ Weight\ [t] + Driver\ Weight\ [t] + Energy\ Storage\ Weight\ [t])$$

We have to notice that, in case of:

- ICE versions, the energy storage weight is given by the storage system filled with max quantity of fuel and AdBlue;
- EV versions, the energy storage weight is given by the weight of the battery pack.

Considering the load factor at the start/end of the mission , the average load factor is:

$$Av.Load\ Factor\ [\%] = \frac{Load\ Factor\ Start\ [\%] + Load\ Factor\ End\ [\%]}{2}$$

It follows that the average transported load is.

$$Average\ Load\ [t] = Max\ Average\ Load\ [t] \times\ Average\ Load\ Factor [\%]$$

Finally, the average operating weight of the vehicle during the mission load is:

$$Av.Operating\ Weight\ [t] =$$
$$= tingge - \ (Powertrain\ W\ \ siosidual\ capacity.apacitback\ tosit\ also\ in\ case\ of\ \ despite\ that, further\ iteratio$$
$$+ Body\ Weight\ [t] + \ Driver\ Weight\ [t] + Energy\ Storage\ Weight\ [t]\ +\ Average\ Load\ [t]$$

4.3.3 Consumption Calculations

For the consumption computation is relevant to know how to make ICE and EV consumptions comparable. This can be easily made taking into account the specific weight of the fuel and its calorific value.

Below are reported the equations used.

$$\text{Specific Consumption } [\frac{kWh}{km\ x\ t}] = \frac{Specific\ Consumption\ \left[\frac{l}{km\ x\ t}\right] \times\ Specific\ Weight\ Diesel\ \left[\frac{kg}{l}\right] x\ \ Calorific\ Value\ Diesel\ \left[\frac{kJ}{kg}\right] x\ 1000}{1000\ x\ 3600}$$

The total consumption for the considered mission has been calculated starting from the calculation of urban and extra urban consumption, and then summing them up.

$$Urban\ Consumption\ [kWh] = Unitary\ Consumption\ [\frac{kWh}{km\ x\ t}] \times\ Urban\ Distance\ [km]\ \times\ Oper.Weight\ [t]$$

$$Extra\ Urban\ Consumption\ [kWh] = Unitary\ Consumption\ \left[\frac{kWh}{km\ x\ t}\right] \times\ Extra\ Urban\ Distance\ [km]\ \ Oper.Weight\ [t]$$

It follows that:

$$Total\ Consumption\ [kWh]\ =\ Urban\ Consumption\ [kWh]\ +\ Extra\ Urban\ Consumption\ [kWh]$$

Here below the CO_2 quantity produced by either the combustion of fuel (conventional vehicles) or the production of electric energy (electric vehicles).

- ICE: 2,650 Kg of CO2 per liter of diesel
- EV: 0,400 kg of CO2 per kWh (from Italian average energetic mix)

Taking these quantities into account, it is possible to calculate the daily quantity of CO_2 emitted by each vehicle operating in the mission.

$$Daily\ Vehicle\ CO2\ Emissions\ ICE\ [kg] =\ Total\ Consumption\ [l]\ x\ 2{,}650\ [kg/l]$$

$$Daily\ Vehicle\ CO2\ Emissions\ EV\ [kg] =\ Total\ Consumption\ [kWh]\ x\ 0{,}400\ [kg/kWh]$$

Considering the dimension of the fleets, the daily quantity of CO_2 emitted by the fleet operating in the mission is:

$$Daily\ Fleet\ CO2\ Emissions\ [kg] =\ Daily\ Vehicle\ CO2\ Emissions\ [kg]\ x\ Dimension\ of\ the\ Fleet\ [n\ vehicles]$$

The yearly CO_2 emissions produced by every mission is.

$$Yearly\ CO2\ Emissions\ [kg] =\ Daily\ Fleet\ CO2\ Emissions\ [kg]\ x\ Yearly\ Working\ Days$$

Finally, to evaluate the environmental impact of fleet electrification, the potential yearly CO_2 saving for each mission has been computed.

$$Yearly\ CO2\ Saving\ [kg] = (Daily\ CO2\ Emissions\ ICE\ [kg] - Daily\ CO2\ Emissions\ EV\ [kg])\ x\ Yearly\ Working\ Days\ [n]$$

4.3.4 Battery Pack Calculations (only for EV versions)

Considering the maximum geometrical space available for the battery pack in the vehicles, the available volume for it is.

$$Volume\ [m3]\ =\ Av.Width\ [m]\ \times\ Av.Height\ [m]\ \times\ Av.Length\ [m]$$

Through the volumetric and gravimetric densities, the weight of the resulting batter is.

$$Weight\ [t]\ = \frac{Volume\ [m^3] \times\ Volumetric\ Density\ [\frac{kWh}{m^3}]}{Gravimetric\ Density\ \left[\frac{kWh}{t}\right]}$$

Then, considering the volumetric density of current Li-Ion batteries, the battery capacity is.

$$Capacity\ [kWh]\ =\ Volume\ [m^3] \times\ Volumetric\ Density\ [\frac{kWh}{m^3}]$$

The recharge time has been estimated, considering current fast charging stations of 150 kW (350 kW fast charging stations will be available soon).

$$Recharge\ Time\ [h] = \frac{Capacity\ [kWh]}{150\ [kW]}$$

Taking into account the capacity of the battery and the consumption required for the mission, the residual energy at the end of the mission is.

$$Residual\ Energy\ [\%] = \frac{Capacity\ [kWh] - Total\ Consumption\ [kWh]}{Capacity\ [kWh]}$$

4.3.5 Optimization (only for EV versions)

In case of vehicles featuring modular battery technology, it may be possible to further reduce consumptions. In fact, the total consumptions obtained comes from the hypothesis that the vehicles carries the maximum battery volume, and then weight, possible. On one side, this ensures the maximum range; on the other side, if such range is not exploited, carrying additional battery volume and weight implies higher energy consumptions.

From the total mission consumption, it has been possible to go backward, estimating the required battery capacity. It has been computed considering the total mission consumption and adding a 10% of "safety capacity", to make sure the vehicle will be able to come back to the depot also in case of unexpected traffic issues.

It follow that, in the ideal case, the vehicle will finish the mission with a 10% of residual energy. Through several iterations, carried out through the Excel Solver, the minimum required battery weight is calculated.

$$Required\ Battery\ Capacity\ [kWh] = 1{,}10\ x\ Total\ Consumption\ [kWh]$$

$$Required\ Battery\ Volume\ [m3] = \frac{Required\ Battery\ Capacity\ [kWh]}{Volumetric\ Density\ \left[\frac{kWh}{m^3}\right]}$$

$$Required\ Battery\ Length\ [m] = \frac{Required\ Battery\ Volume\ [m3]}{Av.Width\ [m]\ x\ Av.Height[m]}$$

$$Required\ Battery\ Weight\ [t] = \frac{Required\ Battery\ Capacity\ [kWh]}{Gravimetric\ Density\ \left[\frac{kWh}{t}\right]}$$

$$\begin{aligned} Optimized\ Average\ Operating\ Weight\ [t] \\ = Powertrain\ Weight\ [t] + Body\ Weight\ [t] + Driver\ Weight\ [t] \\ + Required\ Battery\ Weight\ [t] + Av.Load\ [t] \end{aligned}$$

At this point, the consumption after the optimization can be estimated.

$$\begin{aligned} & Optimized\ Urban\ Consumption\ [kWh] \\ & = \frac{Specific\ Consumption\ \left[\frac{Wh}{km\ x\ t}\right] x\ Urban\ Distance\ [km] x\ Optimized\ Average\ Operating\ Weight\ [t]}{1000} \end{aligned}$$

$$\begin{aligned} & Optimized\ Extra\ Urban\ Consumption(i)[kWh] \\ & = \frac{Specific\ Consumption\ \left[\frac{Wh}{km\ x\ t}\right] x\ Extra\ Urban\ Distance\ [km] x\ Optimized\ Average\ Operating\ Weight\ [t]}{1000} \\ & = \end{aligned}$$

$$Optimized\ Total\ Consumption(i)[kWh] = Urban\ Consumption\ (i)[kWh] + Extra\ Urban\ Consumption\ (i)[kWh]$$

The energy saving produced by the optimization has been calculated. Please notice that it is a negative number.

$$\Delta\ Consumption\ [kWh] = Optimized\ Total\ Consumption\ (i)[kWh] - Total\ Consumption\ [kWh]$$

Finally, the same quantity expressed in percentage has been calculated.

$$\Delta\ Consumption[\%] = \frac{\Delta\ Consumption\ [kWh]}{Total\ Consumption\ [kWh]}$$

4.4 Results

Finally, it is time to show and analyze the results. What has been done is the application of the model for three realistic scenarios (MDD, LD, GC), then a sort of sensitivity analysis of the several missions towards their main parameters: average speed, urbanity rate, average load factor and stops frequency has been performed.

4.4.1 Selected Scenarios

The following picture show the main characteristic of the distribution mission for Multi drop and Local distribution scenarios.

All scenarios foresees that missions are run on flat road (slop = 0%)

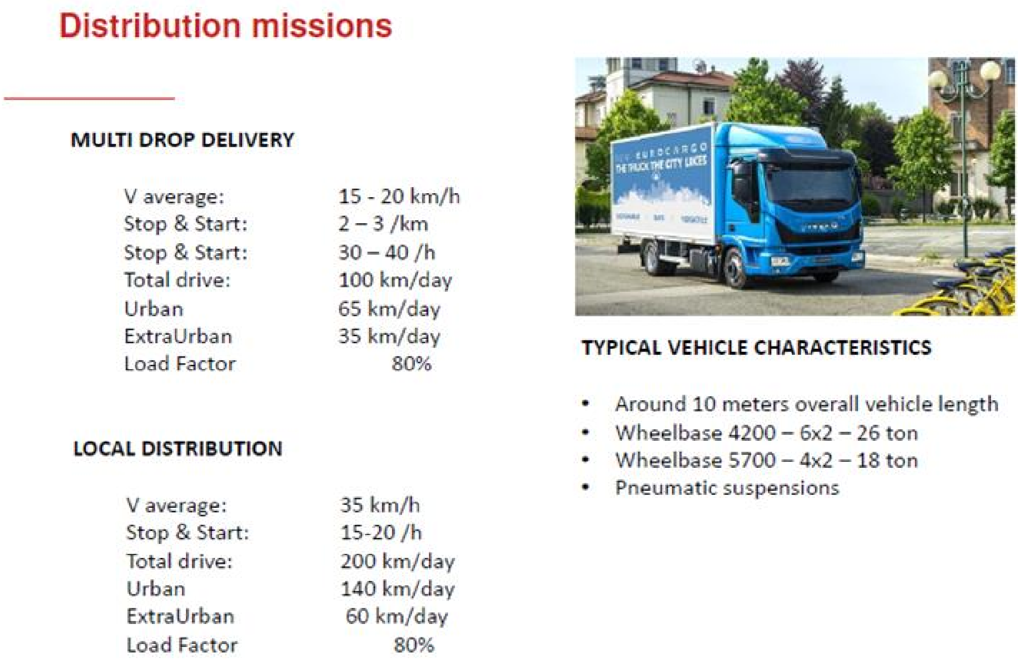


Figure 26: distribution mission parameters. Source: IVECO.

4.4.1.1 Multi Drop

The realistic Multi Drop scenario selected for the application of the model foresee the following input data:

- Urban speed = 15 km/h
- Extraurban speed= 50 km/h
- Extraurban distance = 60 km (that means a distance of WH from the urban area of 30 km
- Service frequency = 30 delivery/h
- Time for delivery = 1,2 min
- Vehicle working time = 8h
- Vehicle type = ICE Eurocargo 18t and EV Eurocrgo 18t
- Fleet dimension = 279 vehicles (see scenario definition)
- Load factor = since we are considering a pure delivery service means that the vehicle starts his service with max load (80%) and will finish the mission with load 0%. This means an average load factor = 40%.

In the following two tables results of model for ICE vehicle and for EV vehicle are shown.

In the table value on yellow cells are input data, while values on green cells are main results.

From the model output we see that overall daily distance is 100 km and interdistance between deliveries is 200m.

The average operating weight is 10,54 ton for ICE and 11.62 ton for EV vehicle (with max battery), difference is due to the different impact of weight of "engine, storage, driveline" of the two vehicle type. Weight difference is around 1 ton, around 10% of the total operating weight.

Total consumption for EV vehicle is 93,827 Kwh (45% of the max battery). But if the battery is sized just as 10% more than what is needed, the required capacity of the battery (optimized) is 86,210 Kwh (saving 8.1%).

Energy spent by the EV vehicle account for 93,827 Kwh against 281,96 Kwh for ICE vehicle with a saving of 66%.

Saving of CO_2 with EV is around 50%.

The number of recharging station for the overall fleet, considering a recharging period of 8h, is of 10 units (with power of 150 Kw).

Total amount of energy needed for the yearly fleet operation account for 5,759 Gwh that compared with the average energy consumption in the city of Turin: 10024 Gwh means 0,057%.

Mission		Vehicle	
Multi Drop Delivery		Eurocargo ICE	
Mission			**Comments**
City		Turin	
Type		Multi Drop Delivery	
Fleet Dimensions [n vehicles]		279	
Yearly Working Days		220	
Urban Speed [km/h]		15,0	
Extra Urban Speed [km/h]		50,0	
Average Speed [km/h]		25,7	
Stop Frequency [1/h]		30	
Stop Duration [min]		1,2	
Stop Duration [sec]		72	
Extra Urban Distance [km]		60	
Mission Duration [h]		8	
Cycle Time (1 Travel + 1 Stop) [min]		2,0	
Travel Duration [min]		0,8	Between two stops
Stops Interdistance [m]		200,0	
Stop Frequency [1/km]		5,0	
Time Extra Urban [h]		1,20	
Time Urban in motion [h]		2,71	
Total Stops		205	
Time Stops [h]		4,09	
Urban Distance [km]		40,9	40,5%
Overall Daily Distance [km]		100,9	
Vehicle			
Type		Eurocargo 4x2 ICE	
Max Admissible Weight [t]		18	
Powertrain Weight [t]		0,786	
Fuel+AdBlue Weight [t]		0,266	
Body weight [t]		4,428	
Driver weight [kg]		80	
Max Available Load [t]		12,440	
Load Factor Mission Start [%]		80%	
Load Mission Start [t]		9,952	
Load Factor Mission End [%]		0%	
Average Load Factor [%]		40,0%	
Average Load [t]		4,976	
Average Delivering Weight [kg]		48,66	
Average Operating Weight [t]		10,54	
Consumptions			
	CO2 Factor Diesel [kg/l]	2,65	
Urban	Specific Consumption ICE [l/100km]	39,1	from COPERT
	Specific Consumption ICE [l/km/t]	0,037	
	Specific Consumption [Wh/km/t]	367,5	
	Urban Consumption [KWh]	158,4	
	Daily Vehicle CO2 Emissions [kg]	42,379	
	Daily Fleet CO2 Emissions [kg]	11823,61	
	Yearly CO2 Emissions [t]	2601	
Extra Urban	Specific Consumption ICE [l/100km]	20,8	from COPERT
	Specific Consumption ICE [l/km/t]	0,020	
	Specific Consumption [Wh/km/t]	195,5	
	Extra Urban Consumption [KWh]	123,6	
	Daily Vehicle CO2 Emissions [kg]	33,072	
	Daily Fleet CO2 Emissions [kg]	9227,09	
	Yearly CO2 Emissions [t]	2030	
Total	Total Consumption [KWh]	281,986	
	Consumption per 100 km [KWh/100km]	279,471	
	Daily Vehicle CO2 Emissions [kg]	75,451	
	Daily Fleet CO2 Emissions [kg]	21050,70	For the city of Turin
	Yearly CO2 Emissions [t]	4631	

Table 18: Multi Drop ICE results.

Mission	Vehicle	
Multi Drop Delivery	Eurocargo EV	
Vehicle		
Type	Eurocargo 4x2 EV	
Max Admissible Weight [t]	18	
EV Powertrain Weight [t]	0,52	
Battery Weight [t]	1,620	
Body weight [t]	4,428	
Driver weight [kg]	80	
Max Available Load [t]	11,352	
Load Factor Mission Start [%]	87,66%	Same load different load factor
Load Mission Start (t)	9,952	
Load Factor Mission End [%]	0,00%	
Average Load Factor [%]	43,8%	
Average Load [t]	4,976	
Average Delivering Weight [kg]	48,66	
Average Operating Weight [t]	11,62	
Consumptions		
CO2 Factor Electricity [kg/kWh]	0,4	From national average energetic mix
Specific Consumption EV [Wh/km/t]	80	
Urban Consumption [KWh]	38,033	
Extra Urban Consumption [KWh]	55,794	
Total Consumption [KWh]	93,827	
Consumption per km [KWh/100km]	92,990	
mission Vehicle CO2 Emissions [kg]	37,531	
Daily Fleet CO2 Emissions [kg]	10471,14	For the city of Turin
Yearly CO2 Emissions [t]	2304	
Battery Pack		
Volumetric Density Li-Ion Battery [kWh/m^3]	150	
Gravimetric Density Li-Ion Battery [kWh/t]	150	
Width [m]	0,6	
Height [m]	0,5	
Length [m]	5,4	2,7 m on each side
Volume Pack[m^3]	1,62	
Effective Volume [m^3]	1,38	85% total volume
Capacity [kWh]	206,55	
Weight [t]	1,62	
Residual Energy Mission End [%]	54,6%	**Batteria OK**
Recharging Stations Power [Kw]	150	
Recharge Time 0-100% [h]	1,38	
Optimization (First Iteration)		
Required Battery Capacity * [kWh]	86,21	Including 10% Safety Charge (=1,1*B45)
Optimized Battery Volume * [m3]	0,57	
Optimized Battery Length * [m]	1,92	
Optimized Battery Weight * [t]	0,68	
Optimized Average Operating Weight [t]	10,68	
Weight Saving * [t]	0,94	
Recharge Time Saving * [h]	0,80	
Urban Consumption (i) [kWh]	34,945	
Extra Urban Consumption (i) (kWh]	51,264	
Total Consumption (i) (with Battery Weight (i)) ** [kWh	86,209	
Δ Consumption (i-1, i) [kWh]	-7,619	
Δ Consumption (i-1, i) [%]	-8,12%	
Results		
Yearly CO_2 Saving [t]	2328	vs ICE
Yearly CO2 Reduction [%]	-50,3%	
Turin Yearly CO2 Emission [kt]	14500,0	
Turin Yearly CO2 Reduction [%]	-0,016%	
Equivalent Battery Packs to be recharged per night	127	
Recharge Time [h]	79,590	To recharge what consumed, not 0-100%
Available Recharge Time [h]	8	In case of recharge only at the deposit
Number of Recharging Stations Needed	10	
Turin Yearly EnergyConsumption (GWh)	10054	
Yearly Fleet Energy Consumption (GWh)	5,759	
Yearly Fleet Energy Consumption (% of total)	0,057%	

Table 19: Multi Drop EV results.

4.4.1.2 Local Distribution

The realistic Local Distribution scenario selected for the application of the model foresee the following input data:

- Urban speed = 30 km/h
- Extraurban speed= 70 km/h
- Extraurban distance = 60 km (that means a distance of WH from the urban area of 30 km
- Service frequency = 15 delivery/h
- Time for delivery = 1,5 min
- Vehicle working time = 8h
- Vehicle type = ICE Eurocargo 18t and EV Eurocrgo 18t
- Fleet dimension = 279 vehicles (see scenario definition)
- Load factor = since we are considering a pure delivery service means that the vehicle starts his service with max load (80%) and will finish the mission with load 0%. This means an average load factor = 40%.

In the following two tables results of model for ICE vehicle and for EV vehicle are shown.

In the table value on yellow cells are input data, while values on green cells are main results.

From the model output we see that Overall daily distance is close to 200 km and interdistance between deliveries is 1.250m. Compared with multidrop mission we have almost double of total distance and interdistance between customer is over 1 km instead of few hundreds of meter.

The average operating weight is the same for the previous scenarios: 10,54 ton for ICE and 11.62 ton for EV vehicle (with max battery), difference is due to the different impact of weight of "engine, storage, driveline" of the two vehicle type. Weight difference is around 1 ton, around 10% of the total operating weight.

Total consumption for EV vehicle requires 180,918 Kwh (86% of the max battery). But if the battery is sized just as 10% more than what is needed, the required capacity of the battery (optimized) is 177,35 Kwh (saving 2.2%).

Energy spent by the EV vehicle account for 180,918 Kwh against 461,188 Kwh for ICE vehicle with a saving of 60%.

Saving of CO_2 with EV is around 41%.

The number of recharging station for the overall fleet, considering a recharging period of 8h, is of 37 units (with power of 150 Kw).

Total amount of energy needed for the yearly fleet operation account for 11,105 Gwh that compared with the average energy consumption in the city of Turin: 10024 Gwh means 0,110%.

As it is quite clear this type of mission is much more demanding that the multidrop mission. Key reason is that reducing stop frequencies (increase interdistance between customer) and increase speed on roads, means much more travelled distance and this mean more consumption.

The scenarios used are quite demanding also as far as the loading factor is concerning, but having 80% of load factor at the beginning of the mission is not the average value recorded in Italy, where usual figures for the loading factor is lower than 50%, in part due to inefficiency of the system, bat also because there are several supply chain that fill the vehicle with volume of goods and not his weight.

This means that there is many missions that can be really managed with EV.

	Mission	Vehicle	
	Local Distribution	Eurocargo ICE	
Mission			**Comments**
City		Turin	
Type		Local Distribution	
Fleet Dimensions [n vehicles]		279	
Yearly Working Days		220	
Urban Speed [km/h]		30,0	
Extra Urban Speed [km/h]		70,0	
Average Speed [km/h]		36,5	
Stop Frequency [1/h]		15	
Stop Duration [min]		1,5	
Stop Duration [sec]		90	
Extra Urban Distance [km]		60	
Mission Duration [h]		8	
Cycle Time (1 Travel + 1 Stop) [min]		4,0	
Travel Duration [min]		2,5	Between two stops
Stops Interdistance [m]		1250,0	
Stop Frequency [1/km]		0,8	
Time Extra Urban [h]		0,86	
Time Urban in motion [h]		4,45	
Total Stops		108	
Time Stops [h]		2,69	
Urban Distance [km]		134,6	69,2%
Overall Daily Distance [km]		194,6	
Vehicle			
Type		Eurocargo 4x2 ICE	
Max Admissible Weight [t]		18	
Powertrain Weight [t]		0,786	
Fuel+AdBlue Weight [t]		0,266	
Body weight [t]		4,428	
Driver weight [kg]		80	
Max Available Load [t]		12,440	
Load Factor Mission Start [%]		80%	
Load (t)		9,952	
Load Factor Mission End [%]		0%	
Average Load Factor [%]		40,0%	
Average Load [t]		4,976	
Average Delivering Weight [kg]		92,45	
Average Operating Weight [t]		10,54	
Consumptions			
CO2 Factor Diesel [kg/l]		2,65	
Urban	Specific Consumption ICE [l/100km]	25,6	from COPERT
	Specific Consumption ICE [l/km/t]	0,024	
	Specific Consumption [Wh/km/t]	240,6	
	Urban Consumption [KWh]	341,2	
	Daily Vehicle CO2 Emissions [kg]	91,281	
	Daily Fleet CO2 Emissions [kg]	25467,44	
	Yearly CO2 Emissions [t]	5603	
Extra Urban	Specific Consumption ICE [l/100km]	20,2	from COPERT
	Specific Consumption ICE [l/km/t]	0,019	
	Specific Consumption [Wh/km/t]	189,9	
	Extra Urban Consumption [KWh]	120,0	
	Daily Vehicle CO2 Emissions [kg]	32,118	
	Daily Fleet CO2 Emissions [kg]	8960,92	
	Yearly CO2 Emissions [t]	1971	
Total	Total Consumption [KWh]	461,188	
	Consumption per 100 km [KWh/100km]	237,049	
	Daily Vehicle CO2 Emissions [kg]	123,399	
	Daily Fleet CO2 Emissions [kg]	34428,36	For the city of Turin
	Yearly CO2 Emissions [t]	7574	

Table 20: Local Distribution ICE results.

Mission	Vehicle	
Local Distribution	Eurocargo EV	
Vehicle		
Type	Eurocargo 4x2 EV	
Max Admissible Weight [t]	18	
EV Powertrain Weight [t]	0,52	
Battery Weight [t]	1,620	
Body weight [t]	4,428	
Driver weight [kg]	80	
Max Available Load [t]	11,352	
Load Factor Mission Start [%]	87,66%	Same load different load factor
Load Mission Start (t)	9,952	
Load Factor Mission End [%]	0,00%	
Average Load Factor [%]	43,8%	
Average Load [t]	4,976	
Average Delivering Weight [kg]	92,45	
Average Operating Weight [t]	11,62	
Consumptions		
CO2 Factor Electricity [kg/kWh]	0,4	From national average energetic mix
Specific Consumption EV [Wh/km/t]	80	
Urban Consumption [KWh]	125,122	
Extra Urban Consumption [KWh]	55,794	
Total Consumption [KWh]	180,916	
Consumption per km [KWh/100km]	92,990	
mission Vehicle CO2 Emissions [kg]	72,367	
Daily Fleet CO2 Emissions [kg]	20190,26	For the city of Turin
Yearly CO2 Emissions [t]	4442	
Battery Pack		
Volumetric Density Li-Ion Battery [kWh/m^3]	150	
Gravimetric Density Li-Ion Battery [kWh/t]	150	
Width [m]	0,6	
Height [m]	0,5	
Length [m]	5,4	2,7 m on each side
Volume Pack[m^3]	1,62	
Effective Volume [m^3]	1,38	85% total volume
Capacity [kWh]	206,55	
Weight [t]	1,62	
Residual Energy Mission End [%]	12,4%	**Batteria OK**
Recharging Stations Power [Kw]	150	
Recharge Time 0-100% [h]	1,38	
Optimization (First Iteration)		
Required Battery Capacity * [kWh]	169,14	Including 10% Safety Charge (=1,1*B45)
Optimized Battery Volume * [m3]	1,13	
Optimized Battery Length * [m]	3,76	
Optimized Battery Weight * [t]	1,33	
Optimized Average Operating Weight [t]	11,33	
Weight Saving * [t]	0,29	
Recharge Time Saving * [h]	0,25	
Urban Consumption (i) [kWh]	121,964	
Extra Urban Consumption (i) (kWh)	54,386	
Total Consumption (i) (with Battery Weight (i)) ** [kW	176,350	
Δ Consumption (i-1, i) [kWh]	-4,567	
Δ Consumption (i-1, i) [%]	-2,52%	
Results		
Yearly CO_2 Saving [t]	3132	vs ICE
Yearly CO2 Reduction [%]	-41,4%	
Turin Yearly CO2 Emission [kt]	14500,0	
Turin Yearly CO2 Reduction [%]	-0,022%	
Equivalent Battery Packs to be recharged per night	245	
Recharge Time [h]	295,346	To recharge what consumed, not 0-100%
Available Recharge Time [h]	8	In case of recharge only at the deposit
Number of Recharging Stations Needed	37	
Turin Yearly EnergyConsumption (GWh)	10054	
Yearly Fleet Energy Consumption (GWh)	11,105	
Yearly Fleet Energy Consumption (% of total)	0,110%	

Table 21: Local Distribution EV results.

4.4.1.3 Garbage Collection

In the following picture the main characteristics of the mission is shown.

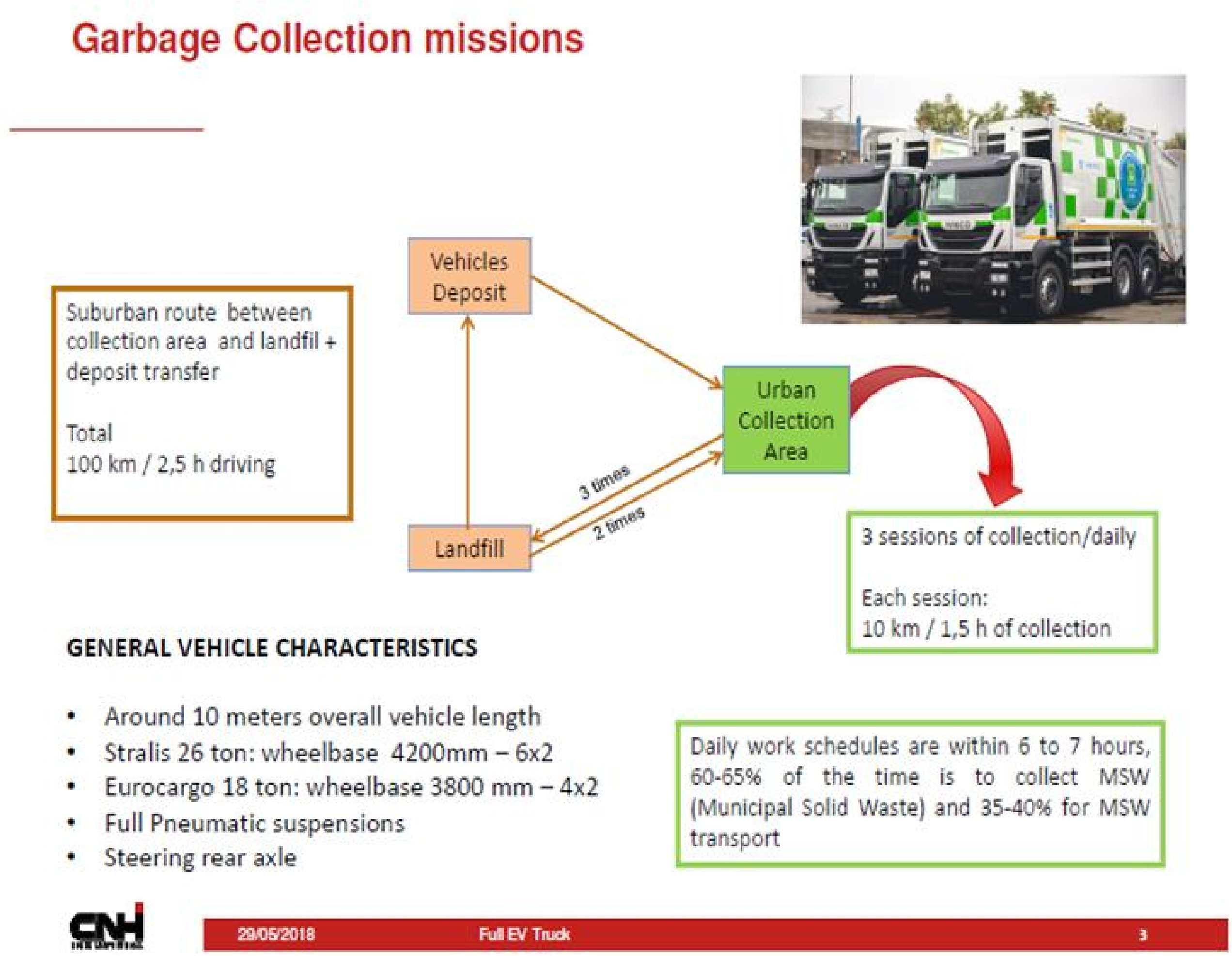


Figure 27: Garbage Collection parameters. Source: IVECO.

The realistic garbage collection scenario selected for the application of the model foresee the following input data:

- Urban speed = 15 km/h
- Extraurban speed= 40 km/h
- Extraurban distance = 100 km
- Service frequency = 48 delivery/h
- Time for delivery = 1 min
- Vehicle working time = 7h (2,5h for transfer and 4.5 for 3 session of collection)
- Vehicle type = ICE Stralis 26t and EV Stralis 26t
- Fleet dimension = 144 vehicles (see scenario definition)
- Load factor = since we are considering a pure collection service means that the vehicle start his service with 0 load (0%) and will finish the mission with max load (93,5%). The computation of average load factor takes into account that there are 4 transfer between landfill, collection area and depot made with

empty vehicle and 3 transfer between collection area and landfill with full load, while the collection tour has an average load factor that is 50%. In end the average load factor is around 40%.

In the following two tables results of model for ICE vehicle and for EV vehicle are shown.

In the table value on yellow cells are input data, while values on green cells are main results.

From the model output we see that Overall daily distance is close to 114 km and interdistance between deliveries is 64 m. Compared with distribution mission, here the frequency has higher value and distance between collection are very short.

The average operating weight is: 14,73 for ICE and 14,84 for EV vehicle (with max battery), difference due to the different impact of weight of “engine, storage, driveline” of the two vehicle type. Weight difference is 110 kg, less than 1% of the total operating weight.

Total consumption for EV vehicle requires 134,8 Kwh (93% of the max battery). But if the battery is sized just as 10% more than what is needed, the required capacity of the battery (optimized) is 135,68 Kwh (no saving because the energy request is 93% of the battery capacity and Optimized size require a 10% of reserve).

Energy spent by the EV vehicle account for 134.82 Kwh against 339,759 Kwh for ICE vehicle with a saving of more than 60%

Saving of CO_2 with EV is around 40%.

The number of recharging station for the overall fleet, considering a recharging period of 8h, is of 16 units (with power of 150 Kw).

Total amount of energy needed for the yearly fleet operation account for 4,313 Gwh that compared with the average energy consumption in the city of Turin: 10054 Gwh means 0,043%.

Mission		Vehicle	
Garbage Collection		Stralis ICE	
Mission			**Comments**
City		Turin	
Type		Garbage Collection	
Fleet Dimensions [n vehicles]		144	
Yearly Working Days		220	
Urban Speed [km/h]		15,0	
Extra Urban Speed [km/h]		40,0	
Average Speed [km/h]		33,4	
Stop Frequency [1/h]		48	
Stop Duration [min]		1	
Stop Duration [sec]		60	
Extra Urban Distance [km]		100	
Mission Duration [h]		7	
Cycle Time (1 Travel + 1 Stop) [min]		1,3	
Travel Duration [min]		0,3	Between two stops
Stops Interdistance [m]		62,5	
Stop Frequency [1/km]		16,0	
Time Extra Urban [h]		2,50	
Time Urban [h]		0,89	
Total Stops		217	
Time Stops [h]		3,61	
Urban Distance [km]		13,5	11,9%
Overall Daily Distance [km]		113,5	
Vehicle			
Type		Stralis 6x2 ICE	
Max Admissible Weight [t]		26	
Powertrain Weight [t]		1,083	
Fuel+AdBlue Weight [t]		0,297	
Body weight [t]		5,870	
Driver weight [kg]		80	
Max Available Load [t]		18,670	
Load Factor Mission Start [%]		0%	
Load Factor Mission End [%]		92,5%	Considering Mission End = Landfill
Average Load Factor [%]		40,4%	Distances D-CA-L = 14,3 km
Average Load [t]		7,548	
Average Weight Collection [kg]		79,77	
Average Operating Weight [t]		14,88	
Consumptions			
CO2 Factor Diesel [kg/l]		2,65	
Urban	Specific Consumption ICE [l/100km]	49,5	from COPERT
	Specific Consumption ICE [l/km/t]	0,033	
	Specific Consumption [Wh/km/t]	329,5	
	Urban Consumption [KWh]	66,3	
	Daily Vehicle CO2 Emissions [kg]	17,750	
	Daily Fleet CO2 Emissions [kg]	2555,94	
	Yearly CO2 Emissions [t]	562	
Extra Urban	Specific Consumption ICE [l/100km]	27,6	from COPERT
	Specific Consumption ICE [l/km/t]	0,019	
	Specific Consumption [Wh/km/t]	183,7	
	Extra Urban Consumption [KWh]	273,4	
	Daily Vehicle CO2 Emissions [kg]	73,140	
	Daily Fleet CO2 Emissions [kg]	10532,16	
	Yearly CO2 Emissions [t]	2317	
Total	Total Consumption [KWh]	339,688	
	Consumption per 100 km [KWh/100km]	2510,397	
	Daily Vehicle CO2 Emissions [kg]	90,890	
	Daily Fleet CO2 Emissions [kg]	13088,10	For the city of Turin
	Yearly CO2 Emissions [t]	2879	

Table 22: Garbage Collection ICE results.

Mission	Vehicle	
Garbage Collection	Stralis EV	
Vehicle		
Type	Stralis 6x2 EV	
Max Admissible Weight [t]	26	
EV Powertrain Weight [t]	0,52	
Battery Weight [t]	0,969	
Body weight [t]	5,87	
Driver weight [kg]	80	
Max Available Load [t]	18,561	
Load Factor Mission Start [%]	0%	
Load Factor Mission End [%]	93,04%	Considering Mission End = Landfill
Average Load Factor [%]	40,7%	Distances D-CA-L = 14,3 km
Average Load [t]	7,548	
Average Weight Collection [kg]	79,77	
Average Operating Weight [t]	14,99	
Consumptions		
CO2 Factor Electricity [kg/kWh]	0,4	From national average energetic mix
Specific Consumption EV [Wh/km/t]	80	
Urban Consumption [KWh]	16,224	
Extra Urban Consumption [KWh]	119,899	
Total Consumption [KWh]	136,123	
Consumption per km [KWh/100km]	119,899	
Daily Vehicle CO2 Emissions [kg]	54,449	
Daily Fleet CO2 Emissions [kg]	7840,66	For the city of Turin
Yearly CO2 Emissions [t]	1725	
Battery Pack		
Volumetric Density Li-Ion Battery [kWh/m^3]	150	
Gravimetric Density Li-Ion Battery [kWh/t]	150	
Width [m]	0,6	
Height [m]	0,5	
Length [m]	3,8	1,9 m on each side
Volume Pack [m^3]	1,14	
Effective Volume [m^3]	0,97	
Capacity [kWh]	145,35	
Weight [t]	0,97	
Residual Energy Mission End [%]	6,3%	**Batteria OK**
Recharging Stations Power [Kw]	150	
Recharge Time 0-100% [h]	0,97	
Optimization (First Iteration)		
Required Battery Capacity * [kWh]	137,12	Including 10% Safety Charge (=1,1*B44)
Optimized Battery Volume * [m3]	0,91	
Optimized Battery Length * [m]	3,05	
Optimized Battery Weight * [t]	1,08	
Optimized Average Operating Weight [t]	15,09	
Weight Saving * [t]	-0,11	
Recharge Time Saving * [h]	0,05	* Calculated on (i-1) weight of the vehicle
Urban Consumption (i) [kWh]	16,339	
Extra Urban Consumption (i) (kWh]	120,751	
Total Consumption (i) (with Battery Weight (i)) ** [kW	137,090	
Δ Consumption (i-1, i) [kWh]	0,967	
Δ Consumption (i-1, i) [%]	0,71%	
Results		
Yearly CO_2 Saving [t]	1154	vs ICE
Yearly CO2 Reduction [%]	-40,1%	
Turin Yearly CO2 Emission [kt]	14500,0	
Turin Yearly CO2 Reduction [%]	-0,008%	
Equivalent Battery Packs to be recharged per night	135	
Recharge Time [h]	122,835	To recharge what consumed, not 0-100%
Available Recharge Time [h]	8	In case of recharge only at the deposit
Number of Recharging Stations Needed	16	
Turin Yearly EnergyConsumption (GWh)	10054	
Yearly Fleet Energy Consumption (GWh)	4,312	
Yearly Fleet Energy Consumption (% of total)	0,043%	

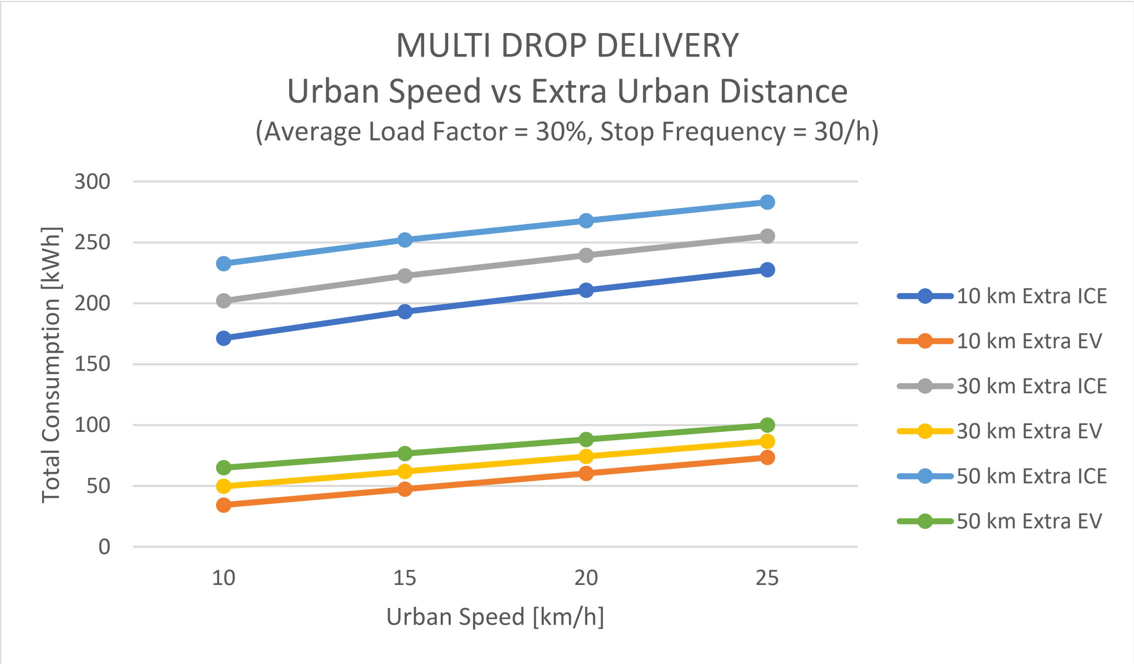
Table 23: Garbage Collection EV results.

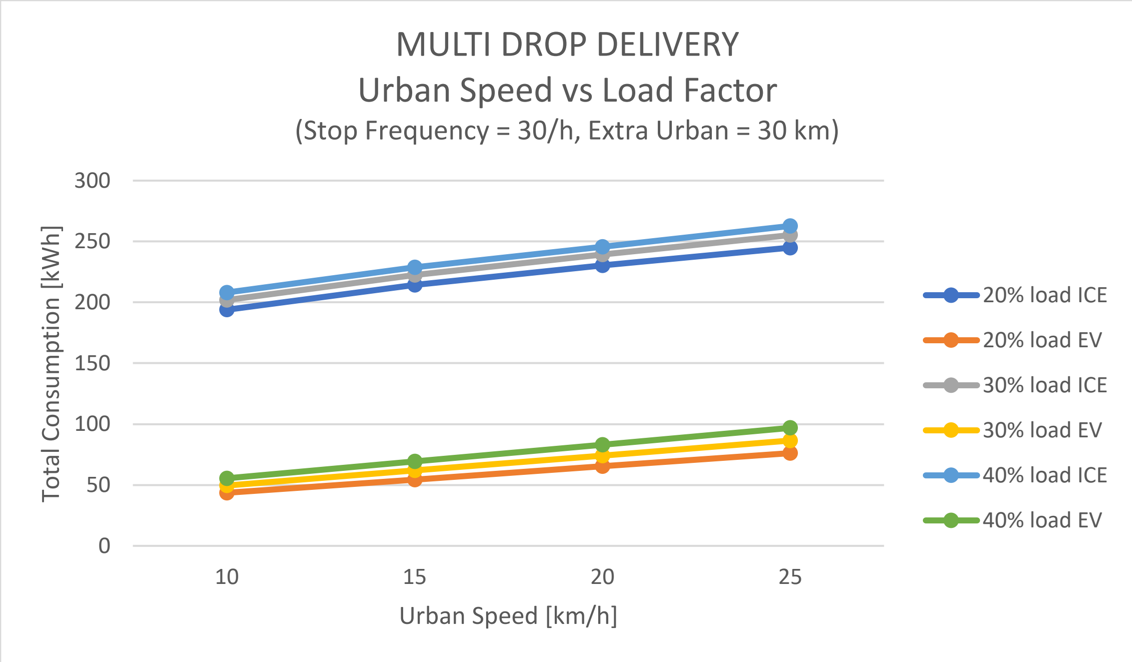
4.4.2 Sensitivity Analysis

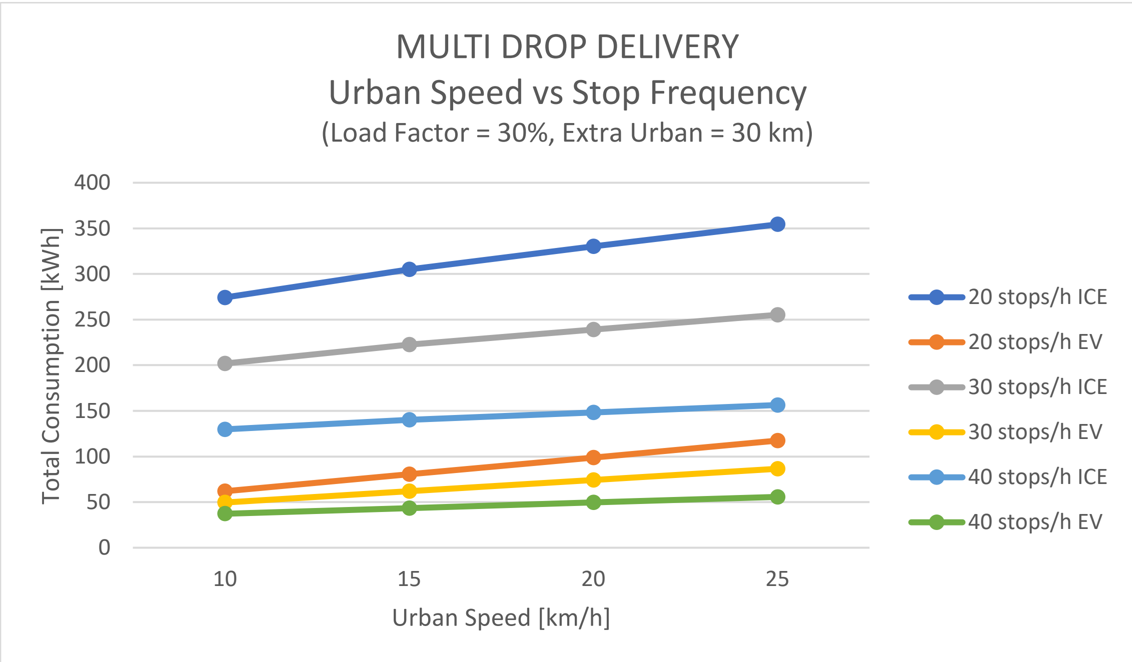
A sensitivity analysis has been performed in order to see how some parameters can influence the total consumption. The parameters picked are:

- the Extra Urban Distance. For distribution missions, it represents the distance between warehouse and delivery area; for garbage collection, it represents the distance between deposit/landfill and collection area;
- the average Load Factor. For distribution missions, it depends on the load factor at the beginning of the mission; for garbage collection, it depends on the load factor at the end of the mission. Also, it always depend on the composition of the route (for example, in garbage collection the average load factor does not correspond to the half of the ending load factor);
- the Stop Frequency. For distribution missions, it depends on the customer to be served; for garbage collection, it depends on the number of stops needed.

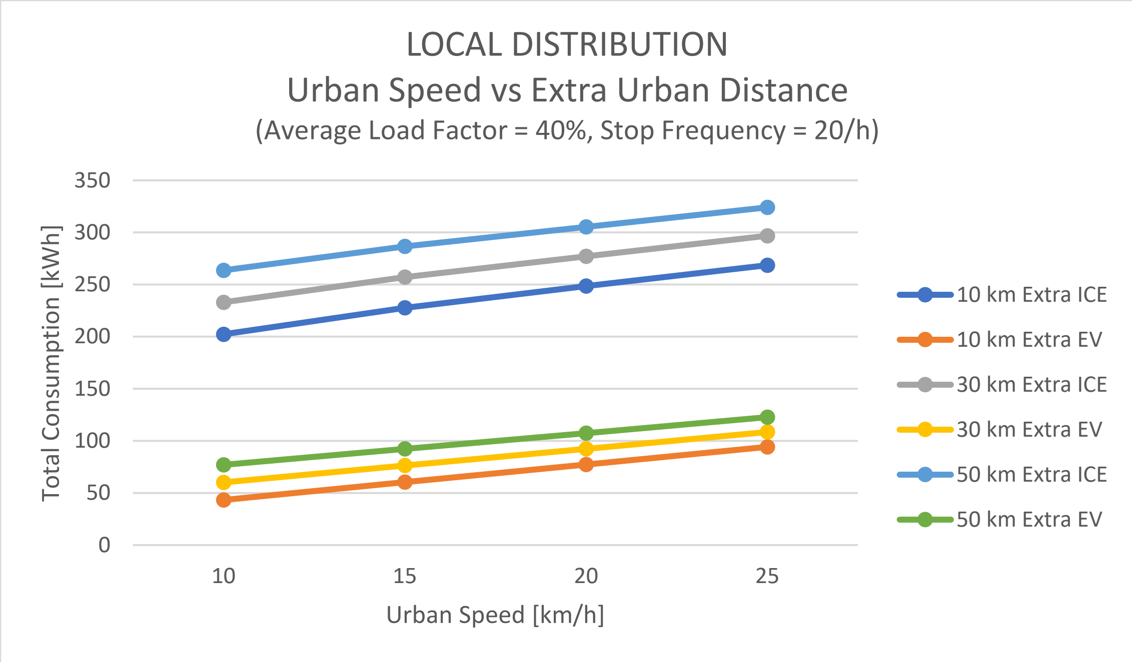
Multi Drop Delivery

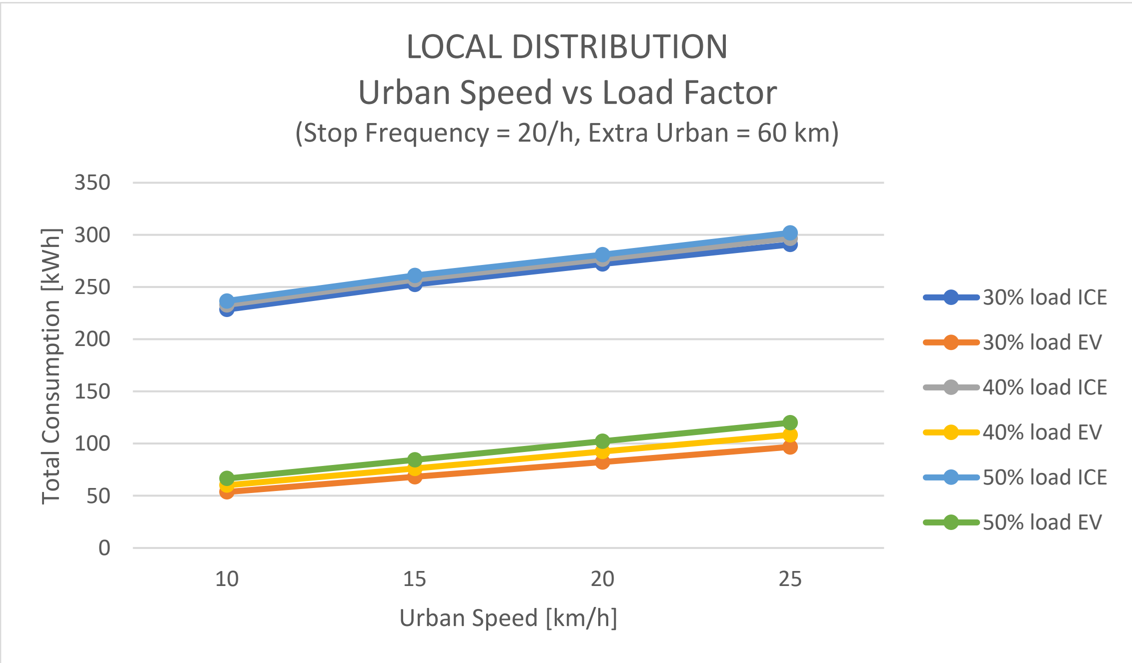


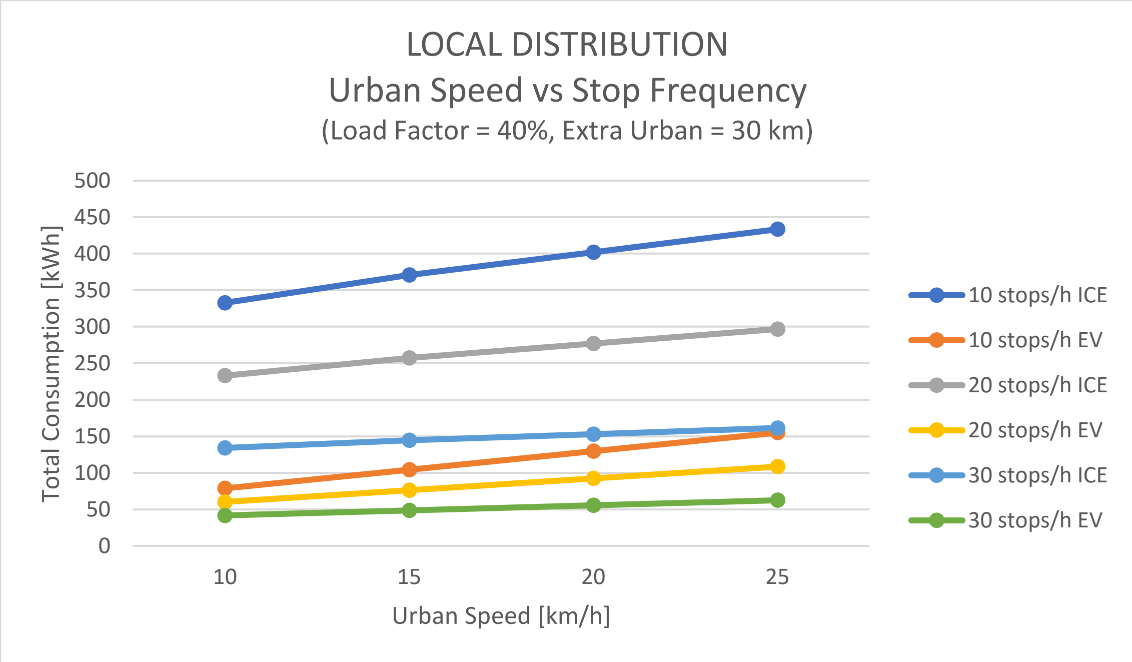




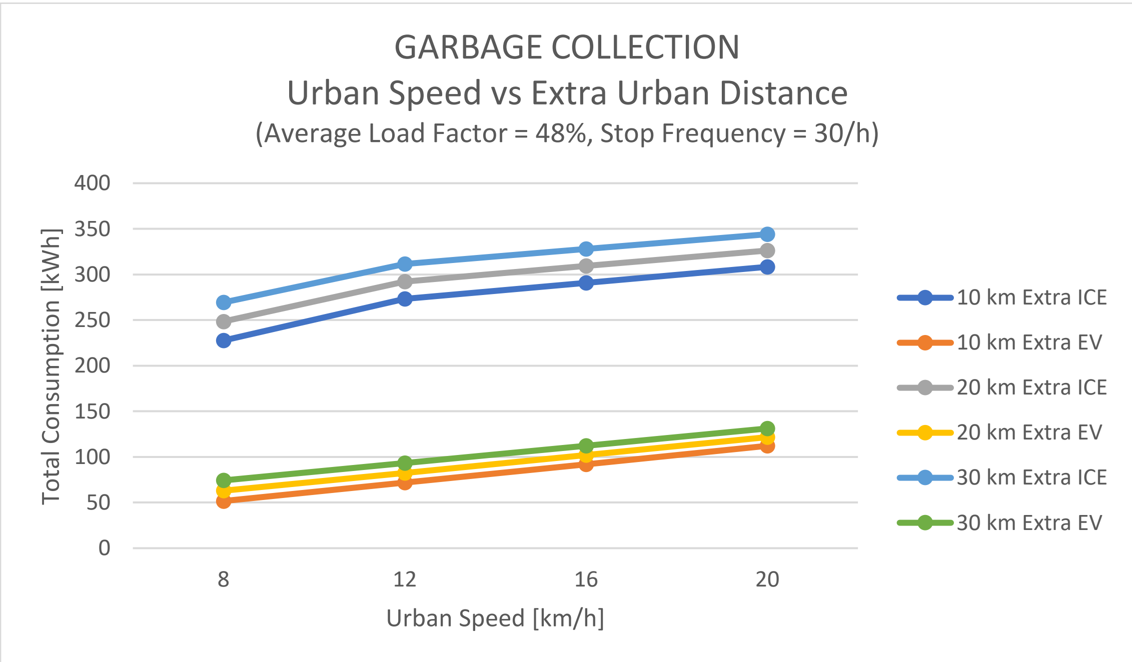
Local Distribution

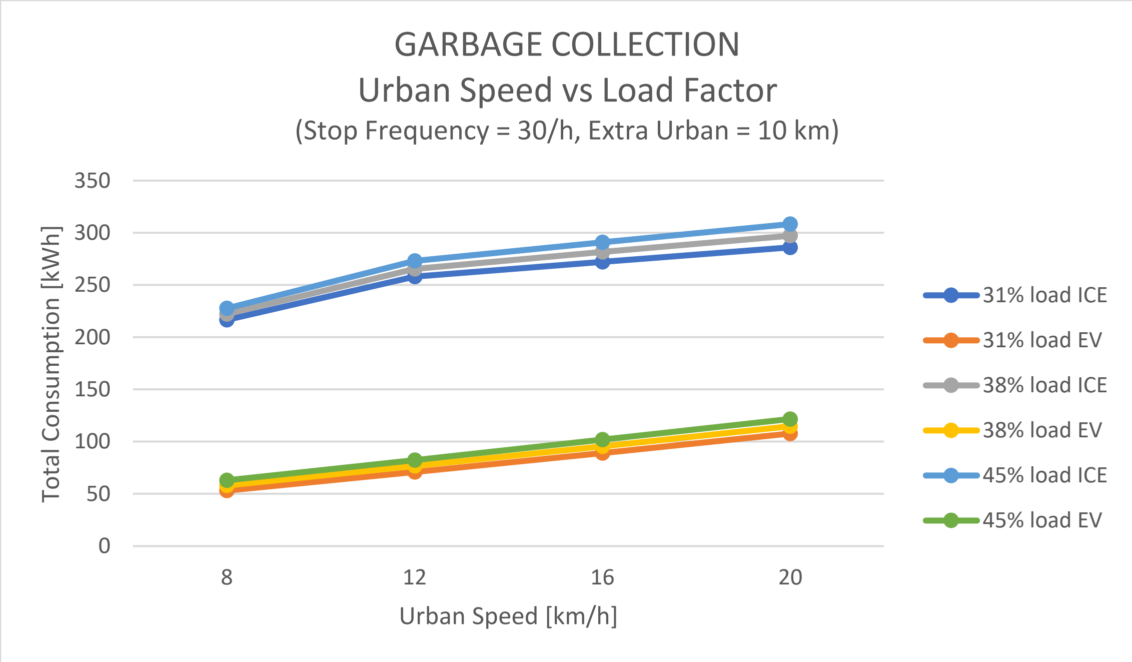

LOCAL DISTRIBUTION
Urban Speed vs Extra Urban Distance
(Average Load Factor = 40%, Stop Frequency = 20/h)
Total Consumption [kWh]
350
300
250
200
150
100
50
0
10
15
20
25
Urban Speed [km/h]
10 km Extra ICE
10 km Extra EV
30 km Extra ICE
30 km Extra EV
50 km Extra ICE
50 km Extra EV

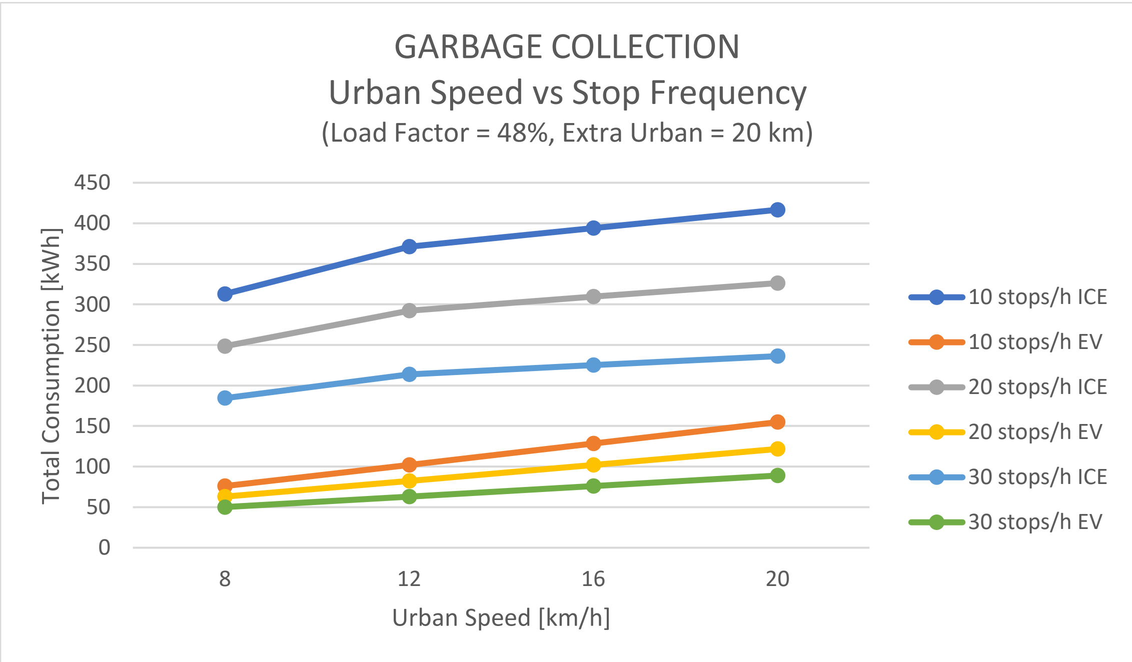

LOCAL DISTRIBUTION
Urban Speed vs Load Factor
(Stop Frequency = 20/h, Extra Urban = 60 km)
Total Consumption [kWh]
350
300
250
200
150
100
50
0
10
15
20
25
Urban Speed [km/h]
30% load ICE
30% load EV
40% load ICE
40% load EV
50% load ICE
50% load EV



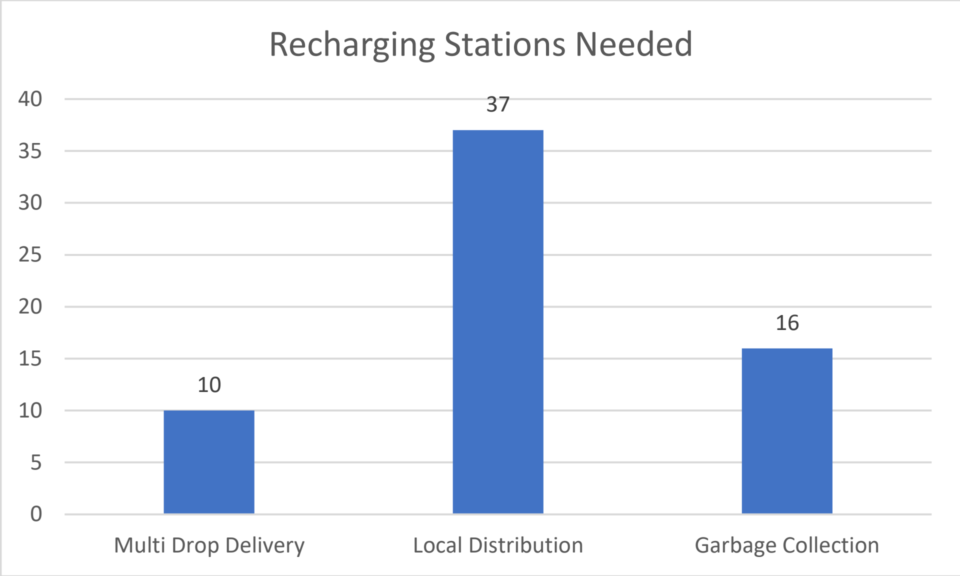
Garbage Collection

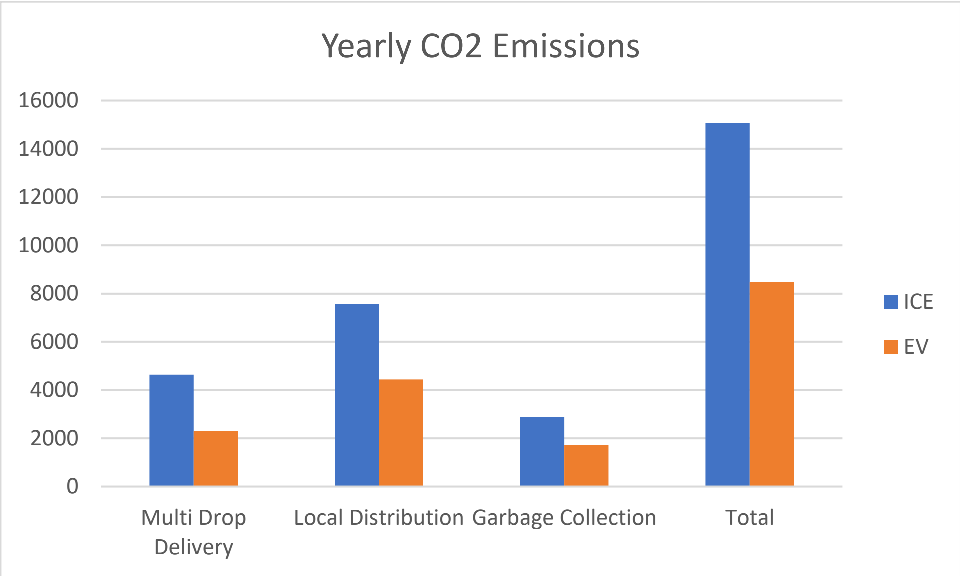






4.4.3 CO2 Savings and Recharging Stations needed





4.4.4 Conclusions

The first good news is that EVs do not suffer from range limitations: with the current battery chemistry technologies, they are able to easily cover every urban mission taken into exam.
The second good news is that EVs allow to save, on average, around 75% of CO_2 emissions. Furthermore, with the current recharging technology (150 kW), the infrastructures needed by the logistic company are not so many. This means that the electrification of the fleet will not require a huge initial investment, and then the payback period will not be long.

From this outcomes, it is possible to state that, with the current state of technology:

- The range of electric trucks results adequate for typical urban operations.
- The electrification of urban logistics operations would allow to cut, in the only metropolitan area of Turin, 6613 tons of CO_2 per year (-43% vs ICE).

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