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Battery electric tractor-trailers in the European Union: A vehicle technology analysis

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Introduction

There is a broad consensus on the need to achieve global net-zero CO_2 emissions by 2050 in order to limit the global mean temperature increase to 1.5°C. To achieve this, the European Union (EU) is taking active steps to make these targets legally binding by enshrining them into a European Climate Law (European Commission, 2020), which would create the legal framework to adopt stringent measures to meet the target across sectors.

Transport, which represents approximately a quarter of Europe's greenhouse gas emissions, has not seen the same gradual decline in emissions as other sectors have in the past (Delgado & Rodríguez, 2018). In particular, the greenhouse gas emissions of road freight transport went unaddressed for decades. It was not until 2019 that the first CO_2 emission standards for new heavy-duty vehicles (HDV) were adopted in the EU. To set the ambition of the standards, the European Commission studied the potential of conventional diesel and natural gas powertrains to deliver CO_2 emissions reductions and did not include zero-emission technologies in its assessment. As a result, the targets set by the standards of a 15% CO_2 reduction in 2025 and a 30% in 2030, relative to 2019, are not in line with the targets set by the Commission or with the targets established by the Paris agreements for 2050 (Rodríguez & Delgado, 2018).

The HDV CO_2 standards will be reviewed by the end of 2022 as more robust data will be available regarding trucks' emissions, fuel economy, and costs of available and new technologies. In addition, the scope of the standards will be extended to cover buses and small lorries and the standardized vehicle simulation tool VECTO will be updated (European Commission, 2018). This provides an opportunity to assess the latest technology developments in zero-emission HDVs, and to include their potential to reduce tailpipe CO_2 emissions into the stringency of the targets for 2030 and beyond.

Tractor-trailers, in long-haul and regional delivery operations, are responsible for over half of the CO_2 emissions of road freight transport (Delgado et al., 2017), making them the most important segment to decarbonize. In addition, tractor-trailers' longer travel

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distances and heavier loads impose additional challenges, making this segment the hardest to decarbonize. Several decarbonization pathways are currently being explored, including battery, fuel-cell, and road-powered electric trucks. In this paper, we focus on battery electric tractor-trailers.

This analysis addresses the following questions:

1. What is the energy consumption and driving range of battery electric tractor-trailers in their typical use profiles?
2. What is the required battery energy capacity to supply the vehicle energy needs and achieve the desired driving range in typical use profiles?
3. What is the impact of the battery electric powertrain on the payload-carrying capacity of the tractor-trailer?
4. What is the impact of extreme weather conditions on the driving range and battery energy capacity requirements for tractor-trailers?
5. What improvements can be expected in the coming decade on the energy consumption and driving range?

To answer these questions, we performed vehicle simulation modeling and analyzed in detail the challenges and opportunities of battery electric technologies applied to tractor-trailers in Europe.

This paper is part of a series of studies on the techno-economic challenges of zero-emission trucks. The results of the analysis of other decarbonization pathways, such as fuel-cell electric technology, will be presented in separate reports.

Methodology

In December 2017, the European Union adopted Regulation (EU) 2017/2400 for the certification of CO_2 emissions and fuel consumption of heavy-duty vehicles. To objectively compare vehicle performance, the certification regulation introduced a standardized vehicle simulation model, called VECTO, which is used to simulate the CO_2 emissions and fuel consumption of the vehicle over a well-defined set of drive cycles and payloads. The VECTO drive cycles applicable to tractor-trailers and the respective payloads used for certification are shown in Figure 1 and Table 1, respectively. These drive cycles and payloads are used in this study.

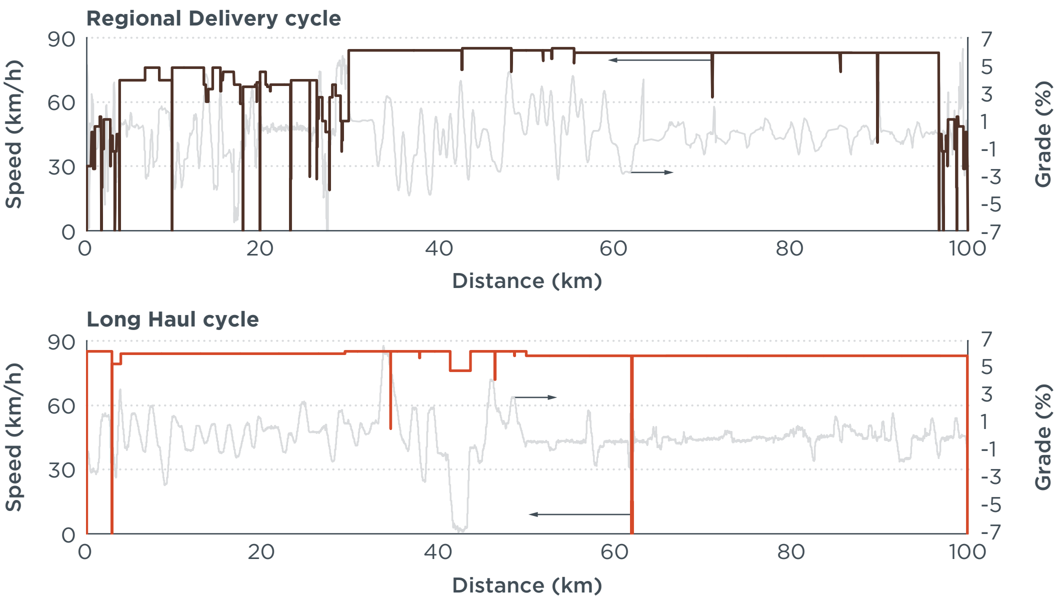

Figure 1. Long Haul and Regional Delivery VECTO cycles

Table 1. VECTO payloads

Mission profile	Low payload	Reference payload
Regional delivery cycle	2,600 kg	12,900 kg
Long-haul cycle	2,600 kg	19,300 kg

Although the European Commission is actively working on expanding the capabilities of VECTO to simulate HDVs with alternative powertrains (Rodríguez & Delgado, 2019), there is not yet a certification approach for the energy consumption and driving range of battery electric HDVs. Manufacturers employ their own methodologies and boundary conditions to estimate the driving range of their products, as used to be the case for the fuel consumption of combustion engine powertrains before the introduction of VECTO-based certification.

In this study, we use a commercial simulation tool called Simcenter Amesim to simulate the performance of the battery electric tractor-trailers. The tool is a multi-physics simulation software that enables the modeling of a wide range of vehicle configurations. As in most vehicle simulation tools, Simcenter Amesim (Siemens, 2020) uses detailed component data to represent the behavior of individual sub-systems, such as the battery, motor, and energy management system, and a network of feedback loops to simulate their interactions with each other and the environment. Detailed performance data for a variety of vehicle and powertrain components are required. The component data used in the study, most notably for the battery and the electric motor, relies on the available libraries in the simulation tool where the different components have been developed and validated in cooperation with industrial partners.

Since the intended purpose of this study is to analyze the performance of battery electric tractor-trailers under VECTO-like conditions, Simcenter Amesim was validated against VECTO using a representative diesel tractor-trailer. Although Simcenter Amesim and VECTO use the same set of underlying physics-based models for estimating fuel consumption, there exist some differences such as the driver model, aerodynamic drag, and rolling resistance coefficient. To estimate the impact of those differences, we provided identical sets of input data to both tools and used them to simulate the fuel consumption of the representative diesel tractor-trailer over the two driving cycles shown in Figure 1.

The results from the two vehicles simulation tools showed good agreement with a difference of 0.9% over the long-haul cycle and 2% over the regional delivery cycle.

Analysis of vehicle technologies impacting the range and energy consumption of battery-electric tractor-trailers

This section provides an overview of four key areas of technology development that have a direct impact on the performance of battery electric tractor-trailers: (1) battery technology, (2) electric driveline configuration, (3) thermal management systems, and (4) road-load technologies. For each technology area, we surveyed the literature to capture well-established facts, recent developments, and expert views on the direction and magnitude of future technological improvements. This information is then used in our simulation model of the battery electric tractor-trailer to quantify the impact on the driving range and energy consumption.

Battery technologies

Overview of battery chemistries considered

Undoubtedly, the most critical issues regarding the deployment of battery electric vehicles, especially heavy-duty vehicles, concern the battery. Lithium-ion (Li-ion) batteries have established themselves as the technology of choice for electric vehicles due to their higher energy density compared to other rechargeable battery systems. In freight vehicles, the battery's energy density is one of the most important parameters, as it directly affects the maximum payload and volume that the vehicle can transport over a given distance. However, there are other critical parameters, such as battery durability, that play an important role in battery selection. Such characteristics depend on the cathode and anode materials, the electrolyte, the separator, and the size and shape of the cell, as well as on the manufacturing process. Still, the chemistry of the cathode of the Li-ion battery remains the most critical design parameter to achieve high energy densities and durability. The three most important Li-ion cathode chemistries are discussed in the following paragraphs.

Lithium nickel manganese cobalt oxide (NMC) is the most popular Li-ion cathode chemistry, as this battery technology is in more than 28% of the global electric vehicles sold and its market share is expected to grow to 63% by 2027 (Boukhalfa & Ravichandran, 2020). The performance of NMC batteries depends on the relative ratios of nickel, manganese, and cobalt oxide. Most commonly, NMC batteries use equal parts of nickel, manganese, and cobalt (NMC-111). The use of nickel-rich cathodes (e.g., NMC-532, NMC-622, NMC-811) increases the energy density of the battery and reduces the amount of high-cost cobalt. However, it can negatively impact battery life (Julien & Mauger, 2020). Although battery cells consisting of an NMC cathode combined with a graphite anode can have energy densities of up to 350 Wh/kg, current NMC cells have energy densities of around 250 Wh/kg and are expected to increase to 300 Wh/kg in the coming years (Ding et al., 2019). Yet, improvements in the anode, such as the addition of silicon or the use of lithium metal, as well as the use of the solid-state electrolytes can significantly boost the energy density of battery cells, opening the door to cell energy densities above 400 Wh/kg (Lu et al., 2019).

The cycle lifetime of batteries, measured in energy throughput throughout their life until they reach 80% of the original charge capacity, is highly dependent on several conditions, including the charge and discharge rates, the depth of discharge, and temperature. NMC cells have good cycle life performance (Miao et al., 2019), exceeding 2,000 cycles at 80% charge capacity retention (Preger et al., 2020). Most manufacturers of electric heavy-duty vehicles, including Daimler (Mercedes-Benz, 2020), MAN (MAN Truck & Bus, 2020), Volvo (Volvo Trucks, 2019), Renault (Renault Trucks, 2020), and E-Force (E-Force AG, 2019), use NMC cells in some vehicles in their portfolio. The cost of NMC cells is dependent on the cell compositions, mainly driven by the high cost of Cobalt. Wentker et al. (2019) report NMC cell cost to be between 70 $/kWh and 90 $/kWh depending on the composition.

Another nickel-rich Li-ion cathode chemistry, lithium nickel cobalt aluminum oxide (NCA), shares similarities with NMC cells in terms of energy density and durability, although with a slight cost disadvantage compared to NMC. Cells with NCA chemistry have typical energy densities above 200 Wh/kg and, like NMC cells, are expected to reach 300 Wh/kg in the coming years (Ding et al., 2019). To date, Tesla is the only vehicle manufacturer employing NCA cells for its batteries. However, to-date it has not been made public whether Tesla intends to use the same battery chemistry for its upcoming electric tractor-trailer Tesla Semi, or if it will employ instead NMC cells. Typical NCA cells cost are comparable to NMC cells at 70 $/kWh–80 $/kWh (Wentker et al., 2019). It is worth mentioning that all the considered battery chemistries witness a similar pack-to-cell cost ratio of 2.4-2.6

Lithium iron phosphate (LFP) is another widely used Li-ion cathode chemistry for electric vehicles. Batteries containing LFP chemistry offer a lower energy density than NMC and NCA chemistries but offer a higher cycle life exceeding 2,500 cycles compared to approximately 1,000–1,500 cycles for the NCA and 2000 cycles for the NMC battery cell (Preger et al., 2020). The higher durability of LFP battery cells enable charge and discharge rates 30% higher than NMC and NCA battery cells (Battery University, 2021), and LFP batteries have significant cost advantage due to their lack of cobalt (Wentker et al., 2019). While LFP batteries have lower energy density at the cell level, they require a less complex integration into packs thanks to their higher resistance to thermal runaway. This in turn increases the gravimetric cell-to-pack ratio (GCTPR) of LFP batteries to 80%–90%, compared to 55%–65% of nickel-based chemistries (X.-G. Yang et al., 2021).

Despite these limitations in cell energy density, there has been recent progress in LFP batteries. Chinese battery producer CATL has been pioneering a cell-to-pack manufacturing approach resulting in an energy density of 160 Wh/kg at the pack level and has managed to reduce costs below 60 $/kWh at the cell level (Manthey, 2020). Another Chinese Battery manufacturer, Guoxuan, has reached 212 Wh/kg LFP cell energy density and aims to reach 260 Wh/kg by the end of 2022 (Kane, 2021). At a GCTPR of 90%, this would situate such a pack in the range of what is expected from nickel-based chemistries. European manufacturers such as VDL (Kane, 2020) and DAF (DAF, 2021), are using LFP batteries in their products.

Table 2 presents an overview of the different lithium-ion chemistries available for HDV application with an evaluation of several key performance indicators.

Table 2. Overview of available Li-ion cathode chemistries for HDV applications.

	NMC	NCA	LFP
Energy density cell (Wh/kg)	240–260	250–300	200–220
GCTPR %	55–65	55–65	80–90
Cycle life (Cycles at 80% capacity retention)	~2,000–2,500	~1,000–1,500	~2,500–3000
Cell Cost ($/kWh)	70–90	70–80	65–80

Modeling of different battery chemistries

In order to assess the impact of the battery chemistry on the driving range of a battery electric tractor-trailer, we defined three batteries with the same energy, power, and voltage at the pack level, but with different cell chemistries: LFP, NCA, and NMC-111. Pre-calibrated cell models exist for these three battery chemistries in Simcenter Amesim, which in turn rely on experimental data collected by Simcenter Amesim's partners, or available in the literature.

The performance of a battery cell is modeled as a function of the battery operating condition, mainly its state of charge (SoC) and temperature. For each battery chemistry, the model uses test data to characterize the open-circuit voltage of the cell, the ohmic resistances, and the entropic coefficient.[1] In addition, the modeling also considers the faradic efficiency, hysteresis modeling, and diffusion and charge transfer losses.[2]

The driving range of the truck is also impacted by the weight of the battery, driven by the battery energy density, as heavier vehicles invariably consume more energy. Therefore, the simulations were also conducted for maximum truck payload, thus, disregarding the effect of the differences in battery weight across the different battery chemistries. The results of this assessment are shown in Table 3, normalized to the

1 The open-circuit voltage is the cell voltage when it is at rest, that is without being charged or discharged. The Ohmic resistance defines the instantaneous voltage drop depending on the charge or discharge current. The entropic coefficient models the voltage change in open-circuit voltage due to temperature change and the heat flow related to this phenomenon.

2 The faradic efficiency takes into account the losses that occurs during charging. The hysteresis modeling takes into account the change of open circuit voltage related to the charge and discharge history. The diffusion and charge transfer losses capture the effect of discharge transients on the battery voltage.

range obtained with the NMC battery, which is the preferred battery chemistry by most European manufacturers.

Table 3. Comparison of the simulated ranges using different battery chemistries over the long-haul cycle. Results are shown normalized to the range obtained with the NMC battery.

Battery chemistry	Normalized range, reference payload	Normalized range, maximum payload
LFP	0.95	0.98
NCA	1.02	1.03
NMC	1	1

The simulated differences in the driving range are not substantial. Li-ion batteries using LFP cells result in a range 2% to 5% lower than NMC batteries, depending on the energy density at the pack level. On the other hand, NCA batteries exhibited a slightly higher range than NMC, between 2% and 3%. To put these values into perspective, those range differences amount to a few kilometers—between 10 km and 25 km— for an electric truck with an approximate 500 km driving range. Based on the previously presented analysis, the rest of this report will focus on NMC battery chemistry.

Driveline configuration

Electric motor technology overview

In this paper, we assess two different types of electric motors: asynchronous induction motors (ASM) and permanent magnet synchronous motors (PMSM). Both motors are coupled to a two-speed transmission and the gear ratios are selected to achieve the same peak torque at the wheel in both motor configurations.

In the case of ASM, a rotating field is generated by alternating current in a stator, which in turn creates a magnetic field in a rotor through electromagnetic induction. To induce an electromotive force, the rotor's magnetic field trails that of the stator resulting in a relative motion referred to as 'slip'. Typically, ASMs have a simple rotor construction, which can result in lower manufacturing costs compared to synchronous motors. However, the motor control is more complex, requiring careful control of the variable frequency in the magnetic field of the stator and the resulting slip. Typically, ASM machines feature a slightly lower efficiency than synchronous motors.

In PMSM machines the rotor's magnetic field relies on permanent magnets, and the rotating magnetic fields in the stator and the rotor move synchronously, eliminating losses associated with slip. However, higher manufacturing costs are encountered due to the rare-earth metals used in the permanent magnets. Higher power density is realized in PMSM in comparison to ASM, offering a more compact mechanical design, higher efficiency at low speeds, and higher torque capabilities.

Modeling of different driveline configurations

In the assessment of both motor technologies, we modeled the driveline with a two-speed gearbox. This selection is used to ensure a sufficient supply of low-end torque (1st gear) while also enabling lower energy consumption at cruising speeds (2nd gear) in a way similar to the VNR Volvo truck (Volvo Trucks, 2020).

The two different driveline configurations are specified so that the trucks can sustain a 65 km/h speed on a 5% road slope. Table 4 summarizes key parameters of the driveline for each motor technology.

Table 4. Summary of driveline configurations.

Motor type	Asynchronous induction motor	Permanent magnet synchronous motor
Maximum power (kW)	350	350
Maximum torque (Nm)	1,000	4,000
Maximum rotational speed (RPM)	10,000	2,500
Nominal voltage (V)	800	800
Peak/continuous torque ratio	1.4	1.4
Transmission system		
Power axle gear ratio	2	1
1st gear ratio	10	5
2nd gear ratio	2.08	1.02
Differential ratio	2	2

The transmission losses of the gearbox are modelled to result in a 98.5% efficiency as estimated by the U.S. Environmental Protection Agency and the U.S. Department of Transportation (U.S. EPA & U.S. DOT, 2016a). The same analysis estimates that gear efficiencies will exceed 99.1% for indirect gears and 99.7% for direct gears in the future. The rear axle is modeled with a lower transmission efficiency at 97% (U.S. EPA & U.S. DOT, 2016b), with the potential increase to 98% in the future.

The electric motor losses are modeled using Amesim's pre-calibrated models for each technology. The resulting efficiency maps, shown in Figure 2, are a function of the motor speed, torque, and voltage.

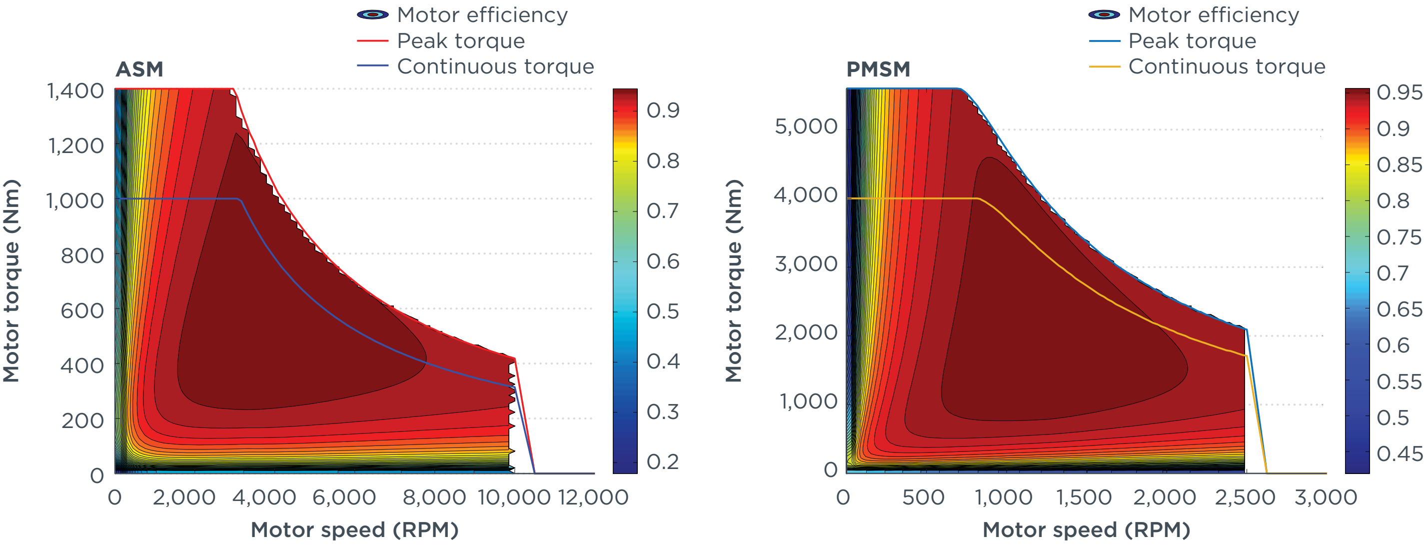

Figure 2. Efficiency map for the two types of electric motors at 800V operating voltage. ASM on the left and PMSM on the right.

The energy performance of each driveline configuration is assessed over the long haul and regional delivery cycles. While the PMSM driveline achieves higher average efficiency throughout both cycles, the difference in the driving range across both driveline configurations was quantified at less than 2% as summarized in Table 5. That being said, PMSM driveline configuration will be used in the rest of this study.

Table 5. Difference in driving range for each driveline configuration over the long haul and regional delivery cycles. Results are shown normalized to the range obtained with the PMSM under reference payloads.

	Drive cycles	
Driveline configuration	Long haul	Regional delivery
ASM	0.982	0.984
PMSM	1	1
% Difference	+1.75%	+1.60%

Road-load technologies

Aerodynamics

The energy dissipated by aerodynamic drag during tractor operation can represent up to 16% of tractor-trailer overall energy needs, as reported in previous ICCT assessments for long-haul applications in Europe (Delgado et al., 2017). Aerodynamic drag energy dissipation is proportional to the square of the vehicle speed, making it particularly significant in long-haul operation due to the higher speeds encountered under such driving conditions. This study simulates a range of tractor-trailer aerodynamic drag coefficients (C_D) from an actual value of 0.5 improving to 0.35 in the future. Such values are expected to be reached by 2030 in the United States by the SuperTruck program (Delgado & Lutsey, 2014), as well as by concept trucks in the European Union, which have achieved C_D values around 0.3 (Kopp, 2012; Kopp et al., 2009). An important difference between VECTO and Simcenter Amesim is the treatment of the aerodynamic drag. VECTO uses a speed-dependent crosswind correction of the air drag area to estimate the average wind conditions (Delgado et al., 2019). Simcenter Amesim, on the other hand, assumes no crosswind is present. To account for this difference, we developed crosswind correction factors for each combination of drive cycle and vehicle using VECTO and applied those to the Simcenter Amesim simulations.

Tires

The energy dissipated by the tires due to rolling friction resistance can represent up to 15% of tractor-trailer overall energy needs over the long-haul cycle (Delgado et al., 2017). This energy load is proportional to the tire rolling resistance coefficient (RRC), which depends on the tractor-trailer weight and speed. The RRC model utilized in this study is defined in a way to mimic the standardized vehicle simulation tool VECTO, as function of the total vehicle mass. Consultants commissioned by the ICCT reported that the RRC reduction rate is at 2% per year (Norris & Escher, 2017). Compared to the reference RRC currently at 0.005, a 27% reduction is expected by 2030 yielding to an RRC value of 0.004, consistent with commercially available tires with an *A* efficiency labeling.

Vehicle weight reduction

Utilizing lightweight materials to reduce vehicle curb weight can impact vehicle energy efficiency and demands in different ways. For tractor-trailers that operate at their maximum allowable payload, light-weighting permits an increase in the maximum allowable payload without changing the total energy consumption of the vehicle. For vehicles that are volume constrained, the light-weighting of the truck's structure enables the use of larger batteries, if needed. Previous studies show that a curb weight reduction over 2 tonnes is possible by 2030, mainly through the substitution of iron and steel with advanced high-strength steel and aluminum/magnesium for various chassis and powertrain components, as well as an additional use of some composite materials (Delgado et al., 2017; Hill et al., 2015).

Thermal management systems

The thermal management of battery electric vehicles is a critical issue due to its impact on the vehicle driving range resulting from the additional energy demand from the battery, especially with the absence of engine heat to warm up the truck cabin. Two main on-board thermal management systems (TMS) are identified: (1) Battery thermal management and (2) Cabin thermal management.

Battery thermal management system

The battery TMS ensures that the temperature of battery cells is within a certain range due to performance and safety considerations. Operating at temperatures outside the recommended range increases the battery impedance and accelerates the different aging phenomena, resulting in charge capacity loss with time (Bandhauer et al., 2011; Kim et al., 2019).

There are several battery TMS technologies deployed in current electric vehicles to maintain the battery within its optimal temperature range. These include air cooling, liquid cooling, phase change material cooling, heat pipes, heat pumps, and positive temperature coefficient resistors (S. Yang et al., 2019). Regardless of the cooling and heating technology, battery TMS can have a measurable impact on the range of electric vehicles as the battery TMS power demand could exceed 5 kW for HDV during hot weather conditions (Basma et al., 2020; Göhlich et al., 2018).

To quantify this impact, we adopt a lumped-thermal model to evaluate the battery cells temperature considering the battery's internal heat generation and heat exchange with its environment. The battery TMS consists of a refrigerated circuit for battery cooling and a heat pump for battery heating, making use of the already-installed heat pump to supply the cabin thermal needs as will be discussed in the next section. A closed-loop controller is designed to maintain the battery temperature at 20°C. The heat pump coefficient of performance[3] (COP) is parameterized using data from the literature for cooling (Dinçer et al., 2017) and for heating (Brodie, 2015) as function of ambient and heat exchanger temperatures. The COP values are validated using a detailed model of the refrigeration circuit.

Cabin thermal management system

For this study, we developed a thermal model of the truck's cabin, considering different modes of heat exchange between the truck cabin and its environment. These include conduction through the cabin's walls, convection, radiation, and solar flux transmission and absorption. A heat pump is considered in this study to supply the cabin thermal needs during both cooling and heating, as it is the most promising technology for electric vehicles (Göhlich et al., 2015) due to its higher COP and, consequently, lower impact on energy consumption in comparison to other technologies.[4] The use of heat pump technology in HDVs is increasing, especially for battery electric buses (Solaris, 2020; Sonnekalb, 2020), and trucks are expected to join this trend as well. The heat pump COP values are adopted from a battery-electric bus application (Basma, 2020). A closed-loop controller is implemented to ensure that the driver's cabin temperature is around 20°C at all times. There are no international regulations that specify the truck cabin thermal comfort conditions yet, while most of the regulations are national. For this sake, a 20℃ cabin target temperature is considered in this study.

3 The coefficient of performance of a heat pump is the ratio of useful heating or cooling provided, measured in energy units, to the work required to operate the system.

4 The heating COP ranges from 1.1 (-10°C) to 3.4 (15 °C) while the cooling COP ranges between 1.59 (40 °C) and 2.51 (25 °C)

Battery electric tractor-trailer driving range and energy consumption

The models developed in this study are utilized to estimate the driving range of the battery electric tractor-trailer for different vehicle technologies and at a variety of operating conditions, based on the vehicle technology analysis conducted in the previous section. Table 6 summarizes the vehicle specifications used for current and future vehicle technologies in the estimation of the tractor-trailer's driving range. Note that the battery weight is a function of the battery size, and in this study, we consider several battery sizes ranging from 300 kWh to 1,000 kWh.

Table 6. Summary of current and future vehicle technologies used to estimate the driving range.

Technology		Current	Future
Road-load	Drag coefficient[5]	0.5	0.35
	Rolling resistance	0.005	0.004
Weight	Tractor	5,850 kg	5,150 kg
	Trailer	7,400 kg	6,208 kg
	Battery pack specific energy	130 Wh/kg	260 Wh/kg
Transmission efficiency	Gearbox gears	98.5%	99.1%
	Differential	97%	98%

In addition, several operating conditions are considered. These include two drive cycles (long haul and regional delivery), several payloads, and three different ambient temperatures (-7°C, 15°C, and 35°C) representing the different EU climate regions and seasons.

One important parameter to consider upon the estimation of the driving range is the initial state of charge (SoC) of the battery at the start of the test or simulation. The battery SoC during the test affects the battery's internal resistance and voltage drop, which can result in an increase in ohmic losses impacting the estimated driving range, particularly at SoC values close to the minimum. For this sake, simulations are carried out with two different initial SoC values: a maximum value of 95 % and a lower value selected so that the SoC at the end of the simulation reaches the minimum allowable SoC at 15%. The driving range is then estimated as the average of these two runs.

Driving range and energy consumption estimation for current and future technologies

We estimated the tractor-trailer driving range and energy consumption for current and future technologies, at different battery sizes, over the long haul and regional delivery cycles. The results, shown in Figure 3 and Figure 4, provide robust estimates that are consistent with the official certification conditions in the European Union. The reference payloads are set at 19,300 kg and 12,900 kg for the long haul and regional delivery cycles, respectively, consistent with the VECTO certification conditions (see Table 1). The ambient temperature is set at 15°C.

For the long-haul cycle presented in Figure 3, the driving range for current tractor-trailer technologies ranges between 174 km and 537 km as the battery size increases from 300 kWh to 1,000 kWh. The increase in the resulting driving range as function of the battery size is not linear since larger batteries increase the weight of the tractor-trailer resulting in additional energy consumption. Furthermore, the cooling or heating requirements are a function of battery size as well. The driving range over the regional delivery cycle,

5 We implemented crosswind corrections consistent with VECTO. This increases the effective drag coefficient over the cycle by 15% to 25%, depending on the drive cycle and the vehicle.

shown in Figure 4, exhibits similar trends in driving range, differing from that over the long-haul cycle by less than 7 km for all battery sizes. This observation, despite the higher transient nature of the regional delivery cycle, is due to a combination of the lower VECTO reference payload and the benefits of regenerative braking.

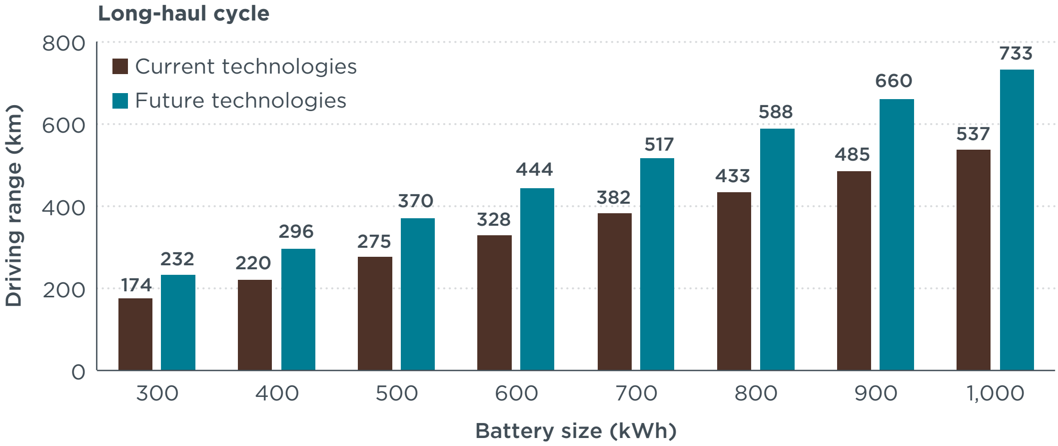

Figure 3. Driving range estimation for current and future technologies over the long-haul drive cycle using the reference payload.

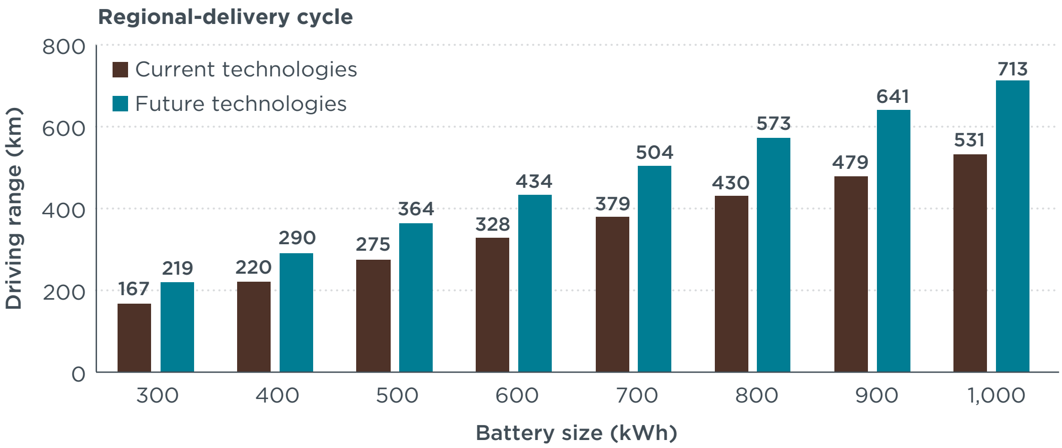

Figure 4. Driving range estimation for current and future technologies over the regional-delivery drive cycle using the reference payload.

Figure 3 and Figure 4 also present the driving range estimation for future tractor-trailer technologies, considering the improvement in battery energy density, transmission efficiency, and road-load technologies. The projected future technology improvements could increase the driving range between 30% and 35%, exceeding 700 km of driving range for the 1000-kWh battery size over both driving cycles. This improvement is mainly driven by a reduction in the total tractor-trailer weight due to light-weighting the chassis components and doubling of the battery's energy density, resulting in a substantial reduction in truck energy consumption, as shown in Figure 5. Consequently, for a fixed range requirement, the results show that the aforementioned future technologies improvement will reduce the battery capacity requirements by approximately 30%. That is, a 500 km range tractor-trailer could be realized by deploying a 700 kWh battery in 2030, compared to the 1,000 kWh required for current vehicle technologies.

Figure 5 shows the distance specific energy consumption, in kWh/km, of the battery electric tractor-trailers for the different battery capacities analyzed, over both drive cycles, and for current and future technologies.

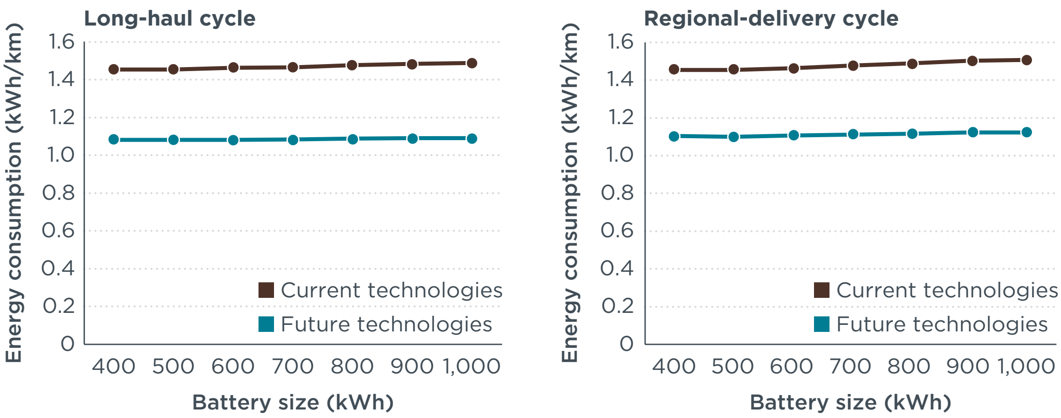

Figure 5. Energy consumption estimation for current and future technologies.

Analysis of the impact of battery weight on payload

The trade-off between electric driving range and maximum allowable payload, that is the payload penalty, is one of the critical issues commonly brought up when discussing the limitations of battery electric tractor-trailers.

The weight of the battery-electric tractor truck is first estimated without the battery. Typical diesel tractor trucks weigh around 7,400 kg (Delgado et al., 2017). The weight of diesel powertrain components to be subtracted is estimated at 2,200 kg, which includes the diesel engine, transmission, and drivetrain (Mareev et al., 2018). The weight of the electric driveline including the motor, inverter, and gearbox is then added and is estimated to be 650 kg (Mareev et al., 2018). Thus, the total tractor truck weight without the battery is around 5,850 kg. We estimated the potential for the light-weighting of the tractor to be around 700 kg, resulting in a future tractor truck weight without the battery of around 5,150 kg. The truck trailer weight is estimated at around 7400 kg, with a potential light-weighting of 1,200 kg, resulting in a 6,200 kg trailer weight by 2030. These weight reduction estimates are consistent with the analysis summarized in the *Road-load technologies* section.

Figure 6 plots the maximum allowable payload as function of the driving range for both current and future vehicle technologies.

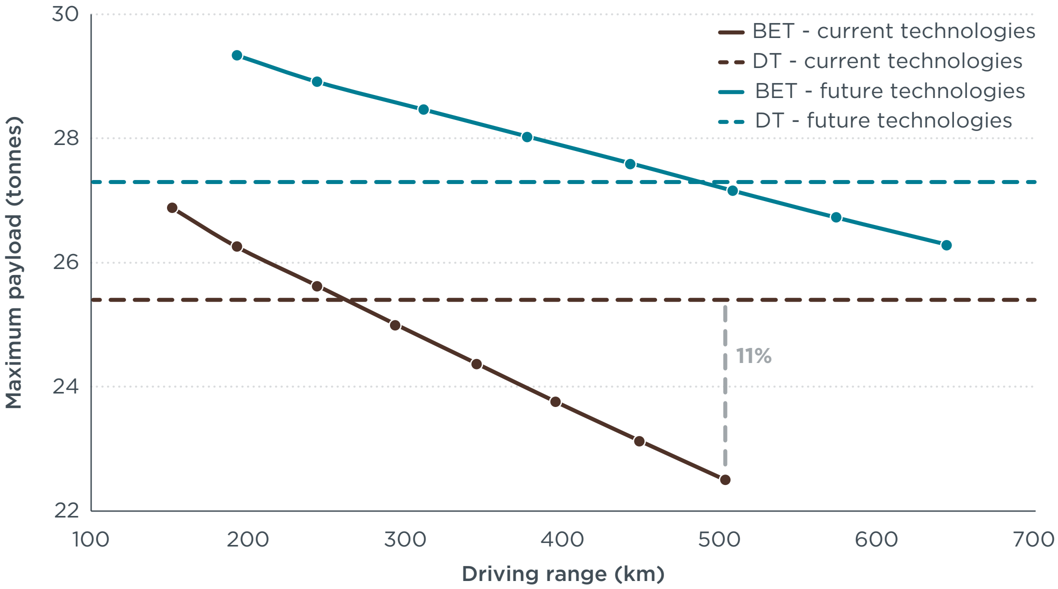

Figure 6. Maximum tractor-trailer payload as function of driving range.

The dashed horizontal lines in Figure 6 represent the maximum payloads of 25,200 kg and 27,100 kg for a diesel tractor-trailer with a gross vehicle weight of 40 tonnes for current and future technologies, respectively (Delgado et al., 2017). The maximum payload of the battery-electric tractor-trailer is estimated with a gross vehicle weight of 42 tonnes, corresponding to the extra allowance in gross vehicle weight introduced for zero-emission heavy-duty technologies by Regulation (EU) 2019/1242 (European Commission, 2019). The maximum payload of the electric truck decreases proportionally with the increase in its driving range due to the increase in battery weight. At a 500 km driving range, which is sufficient to cover 70% of applications without the need for opportunity charging during operation and 95% of cases with a 45-minute charging event during the day (Saboori & Rodríguez, 2021), an 11% reduction in the maximum payload for electric tractor-trailers is observed. However, with future technology improvement, namely chassis light-weighting and battery energy density increase, an electric truck with a 500 km driving range would not result in any payload penalty when compared to its diesel counterpart.

Analysis of payload impact on the driving range

We examined the impact of the payload on the tractor-trailer driving range by considering three different payloads, low, reference, and fully loaded, as summarized in Table 1 The analysis was done over the long-haul cycle and the results are shown in Figure 7.

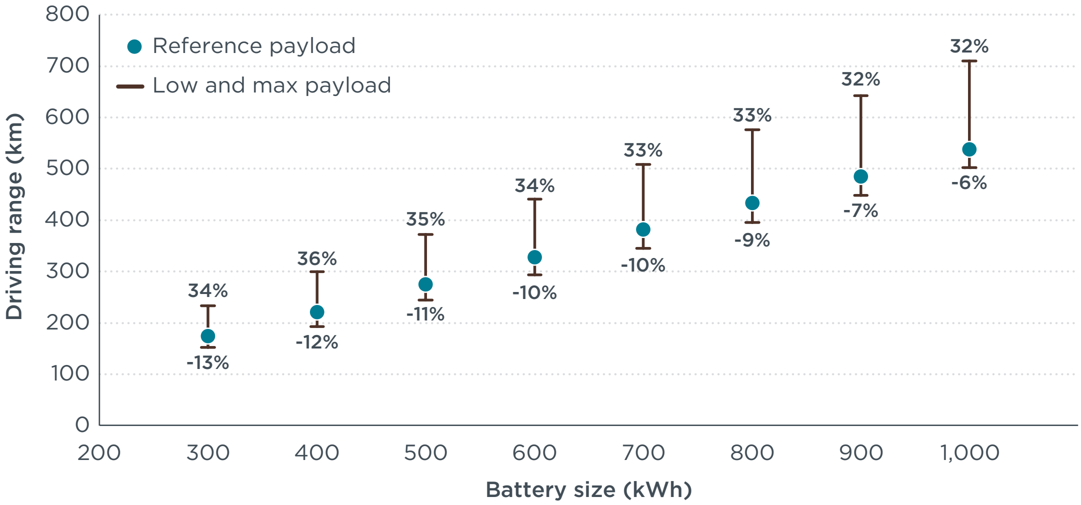

Figure 7. Impact of payload on tractor-trailer driving range over the long-haul cycle (reference payload: 19,300 kg).

In comparison to the reference payload, a low payload improves the driving range by 32%–36% for any battery size. On the contrary, a less substantial reduction in driving range is observed for fully loaded trucks, ranging between 6% and 13%. The results presented in this figure correspond to current vehicle technologies. For future vehicle technologies, similar trends are observed. However, due to the expected reduction in the tractor, trailer, and battery weights, the driving range has a slightly higher sensitivity to the payload, increasing the low payload driving range around 36%–41% and reducing the fully loaded driving range approximately 12%–18%, compared to the case at reference payload.

Analysis of temperature impact on the driving range

The thermal needs in electrified vehicles may have a considerable impact on the driving range, especially under extreme weather conditions. To quantify these impacts, we analyzed three different ambient temperatures representing moderate climate (15°C), cold climate (-7°C), and hot climate (35°C).[6] The analysis presented here corresponds to the long-haul drive cycle at reference payload.

Figure 8 plots the percentage reduction in the vehicle driving range at -7°C and 35°C in comparison to the reference scenario at 15°C ambient temperature. Across the different battery sizes, the driving range reduction does not exceed 9% for extreme climate conditions. This effect on range is a direct consequence of the dependence of the battery's electric properties on temperature and of the energy consumption of the battery and cabin thermal management systems to maintain a temperature of 20°C. For larger battery sizes, the battery TMS requires more energy to maintain the battery cells temperature within the desired range, resulting in a higher impact on the driving range. Hot and cold climate conditions record a similar impact on the driving range despite higher the temperature difference between the ambient and cabin set temperature for cold climate scenario. This is mainly driven by the difference in the coefficient of performance of the battery thermal conditioning circuit.[7] The cabin TMS energy needs are not highly impacted by the battery size, as they are driven by the sun's irradiation, ambient temperature, and cabin geometry. In the 1,000 kWh battery case, the cabin TMS energy consumption is around 15%–50% of the battery TMS energy use.

6 For the hot climate scenario, we consider an average value of solar flux intensity at 1,000 W/m^2 which is not considered in the cold and moderate temperature scenarios.

7 At-7 °C ambient temperature, the COP of the TMS (heating) is around 3. At 35 °C ambient temperature, the COP (cooling) is around 2.

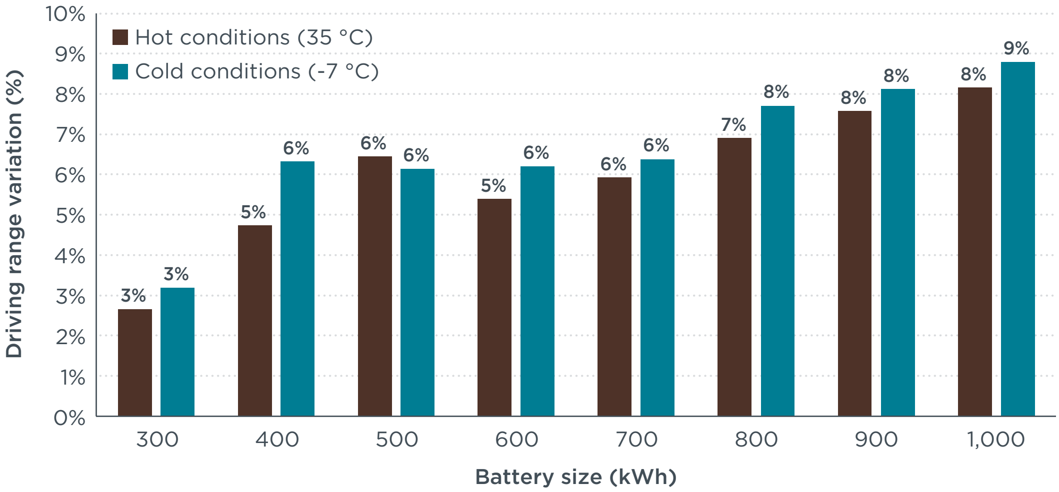

Figure 8: Driving range reduction at different ambient temperatures and battery sizes.

Conclusions and key findings

Long-haul trucks are responsible for the bulk of road freight CO_2 emissions in Europe. Despite the large technology potential to improve the efficiency of trucks powered by internal combustion engines, their feasible reduction in CO_2 emissions is not sufficient to fully decarbonize freight transport at the pace required to achieve climate goals. Thus, zero-emission trucks are necessary to achieve the short and long term CO_2 reduction targets of the European Union.

The current EU HDV CO_2 standards, finalized in 2019, require heavy-duty vehicle manufacturers to reduce the average CO_2 emissions of their fleets by 15% in 2025 and by at least 30% in 2030, compared to 2019. The 2030 target is to be reviewed in 2022. At the time the HDV CO_2 standards were finalized, there was little information available on zero-emission technologies. Thus, the European Commission based the stringency of the currently adopted standards on conventional technologies, namely diesel and natural gas vehicles. Since then, several stakeholders, including most European truck manufacturers, have put in place clear technology pathways for the electrification of on-road freight. The 2022 review of the CO_2 standards presents a latent opportunity to include zero-emissions HDV in the techno-economic assessment underlying the stringency of the CO_2 standards.

This study presents a vehicle technology analysis for battery electric long-haul tractor-trailers. The analysis focuses on the quantification of the energy efficiency and driving range under typical operating conditions, considering several areas of concerns for battery electric long-haul trucks operators. We analyze the vehicle technology potential through detailed vehicle simulation. The battery, powertrain, and thermal management systems are all modeled, validated, and utilized to estimate the vehicle energy efficiency and driving range. We arrive at the following key findings:

» **A 500 km driving range, which is sufficient for the vast majority of applications, can be achieved with a 700 kWh battery energy capacity.** The range anxiety problem for electrified HDV could be overcome by properly estimating the required battery size based on a thorough vehicle energy efficiency analysis. The results presented in this study show that the current driving range of battery electric long-haul tractor-trailers under typical use profiles could exceed 500 km for a battery size of around 1,000 kWh. However, we project that improvements in battery energy density, road-load technologies, and transmission efficiency, will enable substantially smaller batteries around 700 kWh to achieve a 500 km driving range in the future, a 30% reduction in battery energy capacity requirement compared to the base case.

- **A battery electric tractor-trailer with 500 km driving range has a small payload penalty today, with the potential of having no payload penalty in the future.** Battery electric powertrains can achieve a 500 km daily driving range with just a 11% payload penalty in comparison to diesel powertrains, mainly driven by the additional weight of the battery pack. However, scenarios for future technology improvement eliminate the payload penalty and rather generate a payload gain for distances less than 500 km. These differences in the maximum payloads are insignificant since, in most of the cases, trailers reach their volume capacity before reaching their payload capacity. Thus, the payload penalty in electrified tractor-trailers is not a critical issue.
- **Extreme cold and hot temperatures impact the driving range of battery-electric trucks by less than 9% if proper technologies are deployed.** The driving range reduction due to extreme climate conditions is another concern for long-haul tractor-trailers operators. The presented simulation results have shown that, if efficient heat pumps are used, the impact of extreme ambient temperatures of 7°C and 35°C on the driving range does not exceed 9%. These additional energy needs are mostly driven by the thermal management of the battery and, to a lesser extent, by the thermal management of the cabin.

The vehicle technology analysis presented for battery electric long-haul tractor-trailers tackled the energy efficiency and driving range of this technology under a variety of operating conditions and technology improvement. Future studies will examine other decarbonization pathways within this vehicle segment.

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