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Medium-Duty Road Freight Transport—Investigation of Consumption and Greenhouse Gas Emissions of Battery Electric and Fuel Cell Trucks with Model-Based Predictions Until 2050

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Abstract: The present work intends to make a scientific contribution to future drive technology in medium-duty road freight transportation that is as objective and fact-based as possible. In cooperation with a medium-sized forwarding company, 1-day transports, previously driven with diesel trucks, were examined. Using a physically based model, which was first validated by comparing simulated CNG drive data with real-world diesel data, the findings were transferred to battery electric trucks (BETs) and fuel cell trucks (FCETs) and extrapolated to 2050 based on expected technological developments. The model makes statements based on the results of the investigated application regarding specific consumption, greenhouse gas (GHG) emissions, consumption shares and recuperation. The CNG combustion technology (ICET-CNG) serves as a reference. BETs in this application have the lowest emission and consumption values: BET_{2050} will consume a third of the energy and emit a fifth of the GHGs of $ICET\text{-}CNG_{2024}$. The weight of the battery leads to higher consumption values. FCETs have higher fuel consumption due to their longer drive trains. This is partially compensated by their lower weight: $FCET_{2050}$ will consume 40% of the energy and emit a third of the GHGs of $ICET_{2024}$. In long-distance traffic, aerodynamic drag is the dominant consumption factor, accounting for 40%, which should be addressed in further truck development. Recuperation extends the range by 3–7%.

Keywords: battery electric truck; fuel cell truck; specific consumption; greenhouse gas emissions; consumption shares; recuperation; physically based model

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1. Introduction

From 2035, the European Union (EU) will only allow the registration of new cars that are emission-free [1,2]. This is because the traffic and transportation sectors contribute significantly to environmental pollution. In 2021, road transport emitted a total of 740 million tons of carbon dioxide (CO_2), 60% of which came from passenger cars and 40% from freight transport and buses. In contrast to other sectors such as industry, buildings or energy supply, emissions in the transport sector are not showing a downward trend; on the contrary, they have increased considerably since 1990 (+49% in light transportation traffic and +28% in heavy transportation traffic and buses) [3]. The political and ecological pressure on road freight transport is therefore substantial. While electric drive technologies with batteries or hydrogen-powered fuel cells already account for a non-negligible proportion of new passenger vehicle registrations and are offered by many manufacturers (battery electric vehicles (BEVs) and fuel-cell electric vehicles (FCEVs)), there is an almost negligible proportion of new registrations of heavy goods vehicles (either battery electric trucks, BETs, or fuel-cell electric trucks (FCETs); Figure 1). Just 609 heavy-duty BETs were registered in Germany in 2023. This even put Germany in the lead in Europe [4]. The introduction of new drive technologies in medium- and heavy-duty road freight transport is therefore in its early stages.

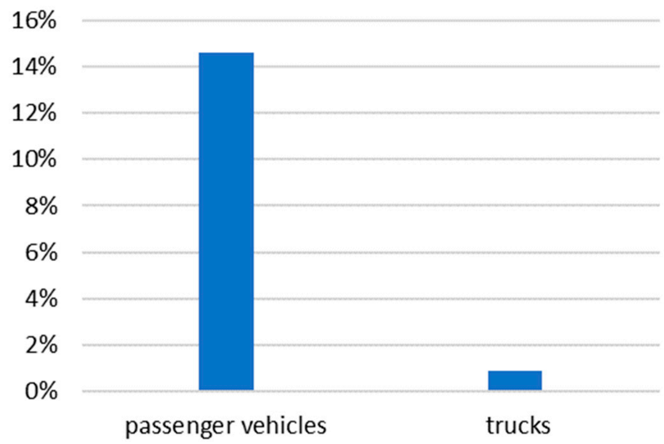


Figure 1. Share of BEVs and BETs (>16 t) among new registrations in their respective class (EU, 2023) [4].

The clear difference in the registration figures points to the discrepancy between aspiration (political objectives) and reality (availability of trucks, usability in operation). Even more than in passenger transport, a number of fundamental and existential questions arise for commercial freight transport in relation to new drive technologies, all the more so as the freight forwarding industry must contend with strict regulations from European governments:

- What will be the costs of BETs and FCETs?
- What ranges can be expected on different tours?
- What additional weights will have to be taken into account for the battery?

In contrast to the established internal-combustion engine vehicle (ICEV) technology, new drive technologies also raise questions for forwarders regarding the infrastructure at their sites/branches: can the required charging current or hydrogen be generated from renewable energies? Can this be carried out independent of time and season and in sufficient quantities? At locations with little wind, does the forwarding business have to be shifted to the night in order to be able to charge during the day? Further questions relate to the routes taken by the trucks: can the infrastructure along the highways be built quickly enough? What are the medium-term costs for electricity and hydrogen on the road? And so on.

The scientific literature is very extensively devoted to the issues of battery-powered electric drive technology. In fact, there is a considerable need for research and development in this area, as the associated drivetrain is completely different from that used in combustion vehicles to date. The new technologies used in batteries (e.g., lithium-ion) and the most commonly used permanently energized electric drives (rare-earth magnets) receive the most attention, but the differences in the transmission train are also significant.

Much more important for the transport and forwarding industry, however, is the lack of factual data. As already shown in Figure 1, there are hardly any BETs or FCETs on the road that can provide direct access to consumption and emission values. Little can be expected from manufacturers during this phase; they fear disclosing information to the competition at an early stage and therefore do not publish quantified results, compounded by the well-known fact that manufacturer data on vehicle consumption and GHG emissions can rarely be reproduced on the road [5–10].

The earlier the development phase, the more the knowledge gaps have to be closed by scientific-technological models in order to back them up step by step with experimental data. This was the approach taken in the BET studies of [11–23] in order to provide predictions for consumption and GHG emissions. BETs and FCETs have been compared by the authors of [24–29]. The literature also pays close attention to the cost side. Both the operating and lifecycle costs as well as the total costs of ownership (TCO) are analyzed in [14,19,25].

Besides costs, the question of driving range also plays a significant role, especially with BETs. The authors of [11,18,20,25,30] give helpful support for finding suitable battery sizes according to the specified length of the transport route. Unfortunately, it is all too rare to find information on dimensioning tolerances so that the truck can be brought home safely even on hilly terrain and/or during the cold season.

Using two examples from the scientific literature, we want to show that the lack of validated data for medium-duty road freight transport leaves a gap in our actual knowledge. Reference [29] is a meta-study that developed an economic model and arrived at results using consumption data from other studies. For both BETs and FCETs, large ranges in consumption are shown, in some cases without providing any comprehensible information on where these consumption data come from or which application/vehicle size they correspond to. Reference [15] is one of the few studies that provides precise consumption data for FCETs for medium-duty road freight transport. However, it also presents a meta-study that derived economic results from adopted consumption values. In contrast, a key feature of our work is to obtain consumption and emission values for BETs and FCETs that are as reliable as possible using application-specific, real-world data and a double-validated model.

The particular challenge facing the current development of drive technology for medium and heavy goods transportation is therefore not so much the lack of scientifically based, differentiated models for trucks, freight, and tours; rather, it is the lack of opportunities to test the model results against reality. This resulting requirement was of particular importance for our work. In the absence of practical data, we postulated the need to verify the model in several stages. The basic technological assumptions of the model can be verified using the extensive database of passenger vehicles. In contrast, the transport-specific model assumptions regarding trucks, freight, and tours can only be compared with real data obtained with the existing ICEV technology. There is a lack of such sound, multi-stage model verifications in the literature. As a result, key questions remain partially or completely unanswered by the current literature:

(1) How does the FCET's longer chain of components affect consumption and GHG emissions?
(2) How does the significantly higher weight of the BET affect consumption and GHG emissions?
(3) How do real-world conditions (hilly terrain, cold seasons, non-optimal driver behavior, etc.) affect fuel consumption and GHG emissions?
(4) How can emissions/consumption be predicted beyond the short-term perspective and limited as quantitatively as possible?
(5) Which consumption shares of the physically acting forces influence the energy balance of the BET and FCET, and how? What conclusions can be drawn from this for the development of new truck drive technologies?

It is precisely these scientific gaps and the resulting questions that provide the motivation for our present work.

In our previous work, we investigated the realistic consumption and greenhouse gas (GHG) emissions of BEVs and FCEVs [5,31]. Based on physical models and reasonable assumptions about technological developments, we could derive predictions for the future up to 2050, which is important as many of today's decisions with regard to new drive technologies will only show their effects in the long term. Building on the results of this prior work, the aim of the current study was to extend the findings to medium-duty road freight transport. Due to the complexity of large trucks, however, it was no longer appropriate to work with standardized vehicle models as before. For both small and large passenger vehicles, we were able to draw on a large amount of data, which enabled us to derive realistic "typical" models for our simulation. We were also able to do the same for light trucks [31]. However, the lack of statistical data for heavy trucks did not allow this in the present work without risking an inadequate representation of reality in the model-based simulation.

The close cooperation with a nationally active freight forwarder enabled us to develop this model. In order to avoid excessive complexity and ensure the relevance of our model, we concentrated on freight forwarding tours that are carried out within one working day. In this way, we avoided the issue of intermediate charging of the battery in the BET, which would have been associated with many assumptions and unresolved issues. In order to be able to draw on a statistically reliable database within the forwarding company, two tours were selected that are driven almost daily in a very similar way (always the same vehicle, always the same route, similar daily rhythm, and similar payload up to a total weight of ca. 25 t). The shorter tour was 330 km long, with a total duration of about 8 h (including freight loading times), while the long tour covered 630 km and took around 12 h. The commercial vehicles used in each case were trucks from the Dutch manufacturer DAF (two-axle tractor units with three-axle trailers, each with a tare weight of ca. 20 t). A detailed description of vehicles, routes, profiles, and payload will be provided in Section 2.

The objective of our work was to determine realistic consumption and GHG emissions of BETs and FCETs in the typical daily forwarding business. In addition, predictions for consumption and GHG emissions up to 2050 were to be derived on the basis of foreseeable technological developments and the assumed development of electricity and hydrogen production. To this end, we first compared the model with reality using the data from the DAF ICEV trucks and their well-documented tours. After this validation, we were able to derive reliable predictions for the new drive technologies on a medium- to long-term time scale in the context of the results of our earlier work.

2. Materials and Methods

2.1. Experimental Approaches

The energy consumption, range, and emissions of a vehicle depend on many influence quantities such as the road gradient, ambient temperatures or the driver's behavior. For fundamental reasons, experimental approaches are not able to make universally valid statements. Rather, the results depend on the respective conditions. Nevertheless, it is the aim of automobile organizations to provide consumers with practicable data that can help them when purchasing a vehicle with regard to technical and ecological values. The ADAC, for example, Europe's largest automobile club, regularly does this by testing frequently purchased vehicles under realistic conditions [6,7]. Other organizations, such as the US Government Office of Energy Efficiency, publish reports that include a collection of consumption data, which in turn are compiled from real-world data [8]. In this way, an attempt is made to counter the lack of significance of individual tests through statistical breadth or by choosing the statistical average. Irrespective of the statistical method, however, the experimental approach is generally unable to provide statements for the future as one can only test physically existing devices.

2.2. Model-Based Approaches

This shortcoming is serious when it comes to dealing with new technologies that will only have an impact over decades—such as electromobility. In our work, we have therefore opted for a model-based approach. Its basis was laid in [5], where we divided the vehicle into its main components, each described by a physical model. All consumption-relevant influences were taken into account (acting forces, efficiency of the components, engine characteristics, temperature dependencies of, e.g., the battery and the tires) and they were parameterized in such a way that consumption and emission values could be determined under different but always reproducible boundary conditions (see Section 3.3 of [5]).

The modelling was structured in such a way that all statements could be derived for four basic vehicle types—small or big passenger vehicles and light or heavy trucks—each equipped with one of three different drive types—BEV, FCEV, or ICEV-CNG (compressed natural gas) (see Figure 2 and Table 1 of [5]). The drivetrains were replaced in a model-compatible manner. For example, the FCEV requires a fuel cell, but this is not necessary in the other two drive types. On the other hand, a BEV needs a battery but not a tank, while an FCEV needs both a battery and a tank; however, the battery can be smaller than in the BEV, although the tank must be suitable for hydrogen at high pressures. All of these drive-specific differences were implemented in the model by complex variants. Of course, the changed weight ratios also had to be taken into account. A detailed description of these model variants is given in Table 1 and Appendix A of [31].

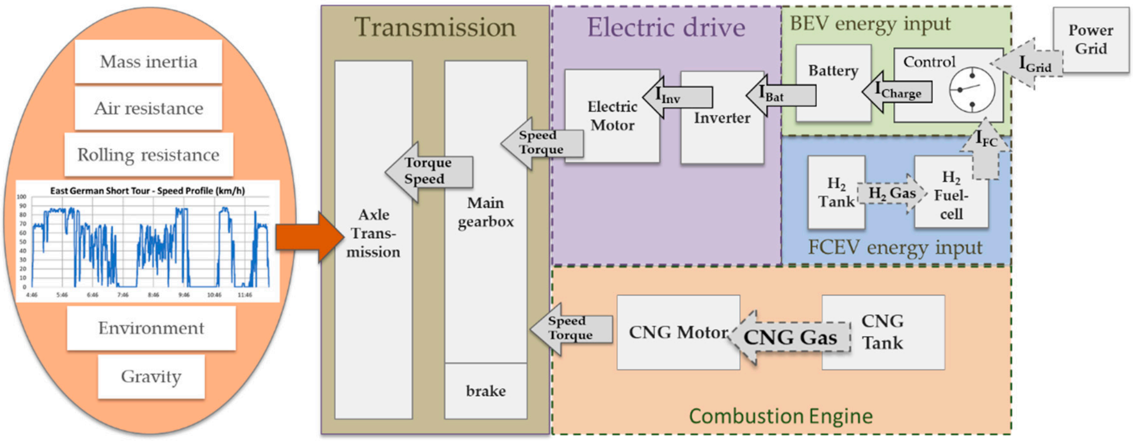


Figure 2. Energy flow diagram of the BEV and FCEV driving cycle model [31].

Table 1. Drive and energy storage technologies considered in the simulation model [31].

Acronym	Drive	Energy Storage
BEV	Electric motor	Battery
FCEV	Electric motor	H_2 fuel cell with tank and battery
ICEV–CNG	ICEV running on CNG	CNG tank

The very good agreement of the simulation results with consumption and GHG emissions as found in several relevant practical tests confirms our modelling and the physical approaches on which it is based. Both passenger and light delivery traffic showed a very good correlation with reality (Section 4.2 of [5], Section 4.5 of [31]). We based our prediction up to 2050 on these verified simulation results from the present.

To extend this work to medium and heavy road freight traffic, we collaborated with a forwarding company operating more than 170 commercial vehicles [32]. In this way, it was possible to generate a realistic vehicle/freight model for typical transportation routes.

2.3. Selection of Transportation Routes

Local distribution is often carried out by large freight forwarders such as UPS, Amazon or DHL. They mostly use small trucks with a total weight of up to 3.5 t, with daily distances of a few 100 km. This segment of road transport has increased considerably in recent years and is therefore justifiably the subject of many comprehensive scientific publications relating to vehicle technology, routes and electric refueling [16,17,33].

We were interested in the more complex and, to date, less extensively investigated medium road freight transport with a total weight of up to 25 t and daily distances up to a maximum of 1,000 km. The focus was on tours that are driven within one day (as already mentioned, multi-day trips would have involved too many assumptions, which would have limited the informative value and generalizability of our work).

Table 2 and Figures 3 and 4 show the details of two tours carried out daily by the forwarding agent. The routes are always the same, whereas the payload varies slightly depending on the order. Typical days were selected. More details can be found in the supplementary data [34].

Table 2. Parameters of the forwarding tours examined (for more details, see Tables S7 and S8 of [34]).

Tour Parameter	Short-Tour	Long-Tour
Date of transport	18 July 2023	24 July 2023
Starting time	04:46:15	00:10:26
Time at end of tour	12:34:12	12:07:41
Duration of tour (h)	7.80	11.95
Distance (km)	330.87	621.17
Elevation of starting/end point (m a.s.l.)	458.4	305.4
Max. elevation point (m a.s.l.)	659.1	481.9
Accumulated elevation meters (m)	2,002.1	3,035.0
Truck type	DAF XF 480	DAF XG 480
Drive technology	ICEV	ICEV
Fuel (reality)	Diesel	Diesel
Fuel (simulation)	CNG	CNG
Payload (kg)	5,100	4,000
Total weight (ICEV truck) (kg)	20,097	19,327
Max. speed (km/h)	88.0	92.0
Max. acceleration (m/s^2)	0.47	0.52

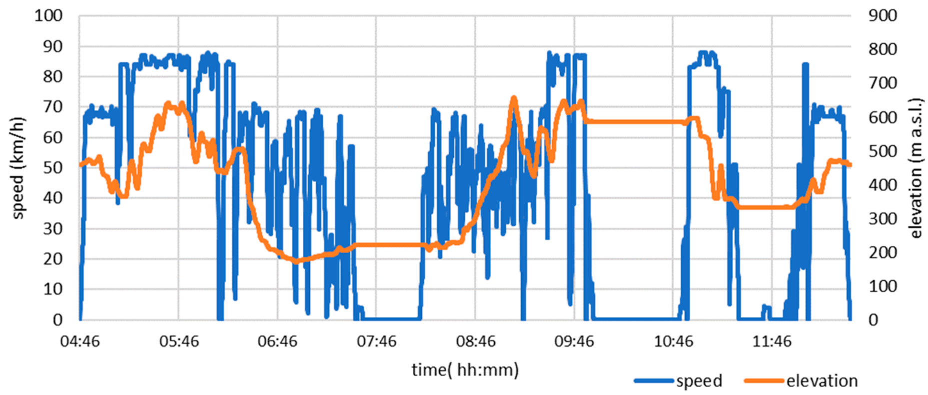


Figure 3. Truck speed and elevation profile of the short tour [34].

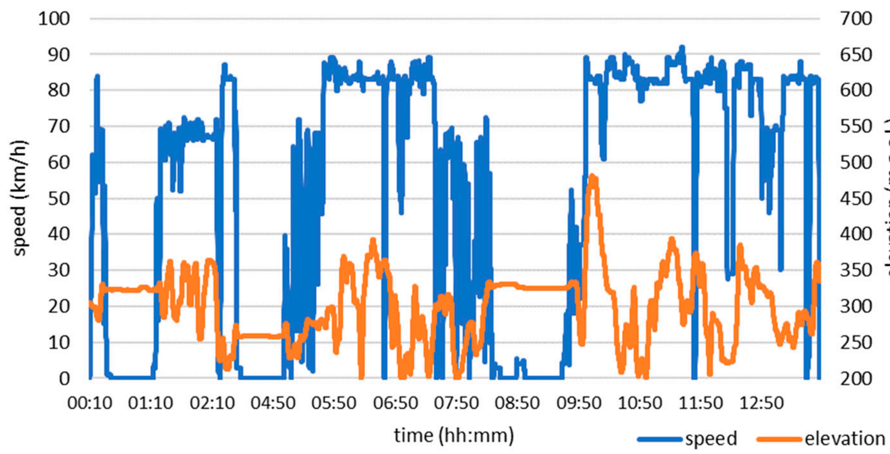


Figure 4. Truck speed and elevation profile of the long tour [34].

The tour and vehicle operating data are recorded via a built-in recording system, which also includes a comprehensive GPS navigation system. These data are recorded almost to the second, stored and continuously transmitted to the forwarder's control center via a satellite-based remote data transmission system. The instantaneous truck speed, which is particularly relevant for consumption, is determined in two independent ways: firstly, from the GPS data, and secondly, by an incremental encoder integrated in the truck's transmission, which measures the drive axle rotation. Together with the tire tread depth measured at short intervals, a speed and distance signal can be derived from this.

The associated height profiles of the forwarding tours provided by the GPS navigator proved to be less accurate in a cross-check. The assignment of GPS coordinates and altitude values was not precise enough. The values available as decimal degree coordinates therefore first had to be converted into UTM coordinates before the exact altitude values could be assigned to them using a worldwide geodetic database [35,36] (see the elevation profiles in Figures 3 and 4). The exact assignment of the altitude values was important because the trips ran through German low-mountain-range landscapes, with some steep descents and ascents. Slight fluctuations in the location coordinates sometimes resulted in significant changes in the elevation values.

2.4. Truck Characteristics

Table 3 gives details on the trucks used on the two representative tours. With the exception of minor deviations, the payload on the tours is always the same (short tour: 5.1 t; long tour: 4 t). The rhythm of loading and unloading as shown in Figure 5 for the short tour was reproduced in the simulation.

Table 3. Diesel truck data [37] (for more details, see Tables S11 and S12 of [38]).

Truck Parameter	Short Tour	Long Tour
	Tractor Unit	
Brand name	DAF XF 480 FT	DAF XG 480 FT
mass of tractor kg (empty tank)	8,607	8,544
Number of axles	2	2
Driven axle	Axle 2	Axle 2
Engine capacity in cm^3	12,902	12,902
Rated power in kW	355	355
Fuel type or energy source	Diesel	Diesel
Axle 1 tires	2 × 315/70R22.5	2 × 315/60R22.5
Axle 2 tires	4 × 315/70R22.5	4 × 295/60R22.5
Length in mm	6,160	6,400
Width in mm	2,550	2,550
Height in mm	3,060–4,000	3,060–4,000
	Trailer	
Mass of trailer in kg (empty)	6,062	6,458
Number of axles	3	3
Max. axle load in kg	9,000	8,000
Size of tires	385/65R22.5	435/50R22.5

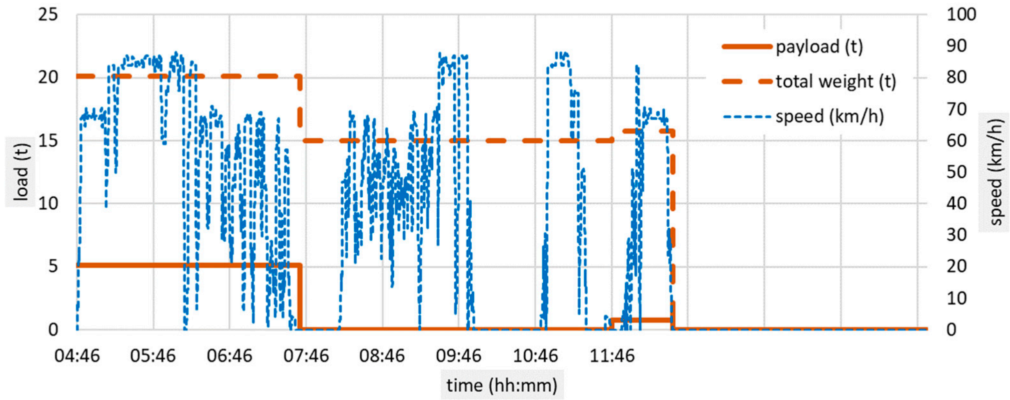


Figure 5. Load and payload on the short tour as a function of driving time [34].

2.5. Vehicle Accessories

The simulation model takes into account the consumption of the vehicle accessory units (air conditioning of the driver's cab, cargo cooling, power steering, seat heating, lighting, and instruments). The nominal consumption of these components was taken from the literature [7,39,40]. Depending on the time of day, season, and driving speed, the ambient temperature and, thus, the consumption of the air conditioning of the driver's cab, cargo cooling, seat heating, the interior and exterior lighting requirements, and the power required for steering the vehicle were determined using characteristic curves. Where these are known from the literature, they were used. Otherwise, plausible assumptions were made (Figure 6). The consumption of freight cooling could be omitted as the freight did not have to be cooled on either investigated forwarding tour.

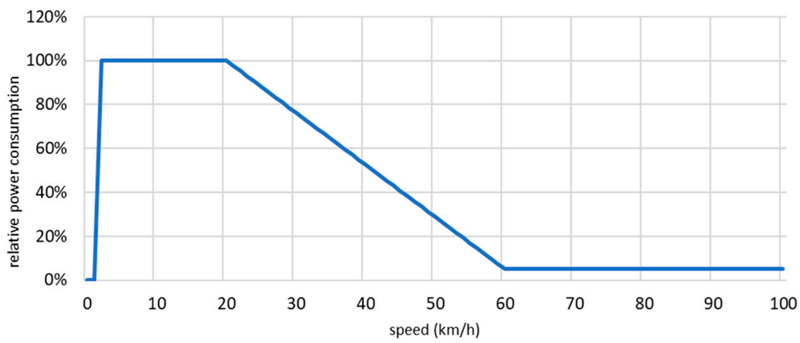


Figure 6. Example of accessory consumption: power steering (relative power) as a function of truck speed. The rated power was 1.6 kW [39], data sheet are shown in the Supplementary Materials (see Table S5 of [41]).

2.6. Technological Development up to 2050

In our earlier study [31], we took a closer look at the technology areas listed in Table 4 for the further development of electric vehicles. Improvements in battery technology power and energy density by 2050 were assumed as listed in Table 5.

Table 4. Technological areas with future improvement to be investigated (Section 3.3 of [31]).

Physical Force	Motor Technology	Motor Control	Energy Storage
Air resistance Rolling resistance Weight	Electric motor CNG engine	Inverter	Battery Fuel cell

Table 5. Previously expected development in battery energy density until 2050 (Section 3.3 and Table 6 of [31]).

Energy Density	Unit	Year		
		2020	2030	2050
Gravimetric	Wh/kg	200	400	750
Volumetric	Wh/L	500	750	1,100

The recent development of battery technology now makes us believe in a less optimistic improvement potential. Various efforts to replace the battery raw material lithium (Li) have attracted particular public attention. As Li is mined and extracted under questionable conditions that are harmful to the environment, efforts aim to replace Li with another chemical material that has similar chemical–physical properties but is more common in nature and can be extracted with less effort. The chemical element that is closest to ${}_{3}Li^{7}$ in terms of its chemical properties is ${}_{11}Na^{23}$, which also has a single electron in its outer electron shell and therefore reacts very similarly to Li. However, it has 16 additional nucleons. While Li is light, with a specific weight of 0.534 g/cm^3, Na has a specific weight of 0.968 g/cm^3 and is therefore almost twice as heavy. Na-ion batteries promise to be significantly cheaper than Li-ion batteries due to the almost unlimited supply of Na. Na can be found all over the world, so intercontinental transportation would become obsolete. Its extraction has been known for centuries and is ecologically unproblematic. Due to these advantages, many developments are currently focusing on Na technology (Table 6).

Table 6. Sodium-Ion-batteries overview to major development projects [42–46].

Company	Country	Cathode	Anode	Electrolyte	Energy Density	Power Density	Cycle Stability
Natron Energy	USA	Prussian blue	Prussian blue	aqueous		12C	25,000
Altris/Northvolt	Sweden	Prussian blue	hard carbon	nonaqueous			
HiNa Battery	China	NaFeMnCuO	anthracite carbon		120		2,000
Novasis Energies	USA	Prussian blue	hard carbon		100–130	10C	500
Tiamat	n.n.	Poly-anionic material			100–120	10C	4,000
Faradion Limited	U.K.		hard carbon	liquid	140–150	3C	1,000

The main drawback of Na, of course, in the context of mobility, is that Na batteries will be larger and heavier. According to the current state of research, we have therefore updated the expected development in battery energy density as shown in Table 7. These updated parameters were used in the further simulations.

Table 7. Updated expected development in battery energy density until 2050.

Energy Density	Unit	Year		
		2024	2030	2050
Gravimetric	Wh/kg	200	300	450
Volumetric	Wh/L	500	650	800

Since our last publication (subsection 3.3.2 of [31]), there has been no significant change in our expectations regarding the further technological development of fuel cell technology. We therefore adopt the values for the FCET parameters from this paper.

However, it should be noted that both battery and fuel cell development are in a phase of dynamic change. Despite the carefulness and evaluation of many scientific studies in this regard, the values set for the period under consideration up to 2050 are to be understood as a prediction. Of course, disruptive inventions, either technologically or based on completely new materials, cannot be part of a fact-based prediction.

2.7. GHG Emission Factors for Fuels and Electricity

The majority of users will have to use electricity from the grid when using electric drive technology. We also make this assumption for forwarding companies, as very few of them will have cheap renewable electricity available at all times of the year, day or night. Assume, e.g., that a forwarding company owns a 1,000 kW_{peak} or 2,000 kW_{peak} photovoltaic system, which are rather large systems. Such PV systems could, respectively, generate around 1 and 2 million kWh of electricity per year in southern Germany. Yet, with a monthly range volume of 1,000,000 km, they would provide only about 3% and 6%, respectively, of the energy required for transport in the winter months and about 15% and 30%, respectively, in the summer months (this assumes a reasonable BET consumption of 1 kWh/km). On average, the PV-generated electricity would only provide 8% and 16%, respectively, of the annually required energy (Figure 7). Even large PV systems fall far short of the actual demand. In addition, the question of how the PV electricity is to be fed into the BET batteries when the trucks are not available for charging during the day still needs to be answered. We therefore consider the assumption justified that freight forwarders will electrify their transports largely by using grid electricity in the foreseeable future.

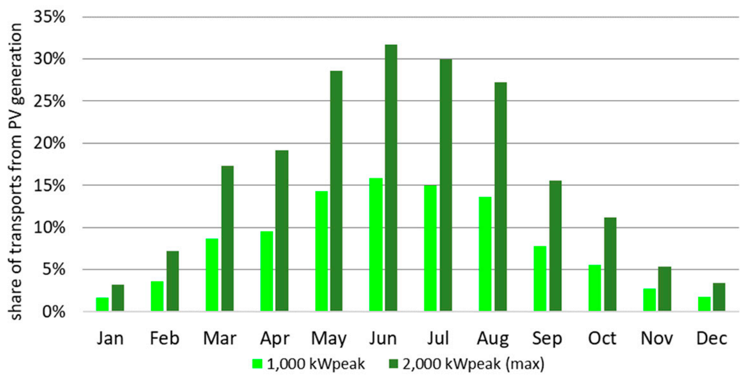


Figure 7. Seasonal share of transportation that can be operated with solar-generated energy. See text for assumptions [32].

As to the electricity generation mix in Germany, the reader is referred to Section 3.4 of [31]. These numbers also had to be updated as Russia's attack on Ukraine had unpredictable and significant effects on the details of electricity generation in Germany and Western Europe. Table 8 shows the adjusted values. The committed phase-out of fossil fuel generation has not materialized as planned. Coal- and oil-fired power plants, some of which had already been closed down, had to be brought back on grid to ensure security of supply. No new findings have emerged in the meantime for the production chains of hydrogen and CNG, but the emission factors for them were recalculated with the new values for the electricity emission factor (Table 8).

Table 8. Updated GHG emission factors [47–49] (for previous estimates, see Section 3.4 of [31], * Germany).

GHG Emission Factors ($g\ CO_2$-Equiv./kWh)	2020/24		2030		2050	
	Previous	Updated	Previous	Updated	Previous	Updated
Electricity *	376	376	225	300	58	125
H_2	301	301	256	284	95	175
CNG	230	230	195	195	76	126

Our simulations, including the results given in Section 3, are based on a tank-to-wheel analysis, i.e., for example, the raw material and energy input for the production or disposal of the trucks are not considered.

3. Results and Discussion

3.1. Model Validation by Comparing Real-World Diesel Trucks with ICEV-CNG Truck Model (ICET-CNG)

The most advanced and ecologically effective combustion-based drive technology is the CNG engine, which we therefore use as a benchmark. The first step on the way to our goal was to compare the simulation results of the ICET-CNG model with the real diesel consumption on the reference tours. Values from the literature were taken for the key consumption-determining parameters such as air and rolling resistance [50,51] and then adjusted as dictated by the state of the art or by measurement results. Where ranges were given in the literature, we placed ourselves in the middle. For example, Ref. [52] gives a range of 0.49 to 0.77 for the air resistance of five-axle semi-trailer trucks. As this study provides very detailed information on the aerodynamics of heavy commercial vehicles but the data date back to 2012, the c_w value was initially set below the mid-point of 0.65.

In contrast to air resistance, the values for the rolling resistance are quite uniform in the literature. We used 0.6% as the starting value in the model [52,53].

Some adjustments also had to be made to the characteristic curves of combustion engines due to technological developments. In Table 4 of [31], we achieved very good results with a maximum efficiency of 39% for the CNG engine. However, a few years ago, DAF launched a new, more economical generation of diesel trucks, the fuel consumption of which is stated to have been reduced by 10% [37,54–57]. Such fuel-efficient trucks were used on the long reference tour, whereas the short tour is still run with old-generation DAF XF trucks.

The simulations were carried out on the basis of the vehicle data (Table 3), tour data (Table 2) and consumption-determining parameters (Table 9). This led to excellent agreement with the real consumption values for both tours (Figure 8). This is surprising given the high complexity of the traffic conditions described.

Table 9. Parameter sets for the dominant variables influencing consumption.

Parameter	Start Parameter Set		Adjusted Parameter Set	
	Short Tour	Long Tour	Short Tour	Long Tour
Air resistance	0.65	0.65	0.63	0.60
Rolling resistance	0.60%	0.60%	0.58%	0.56%
CNG motor efficiency (max.)	39%	39%	39%	42%

The simulation determines the CNG consumption of an ICEV-CNG truck in kg per 100 km whereas the real-world consumption is for a diesel truck and is measured in liters per 100 km. The conversion was made using the empirically known fact that 10 L of diesel corresponds to 9 kg of CNG [58].

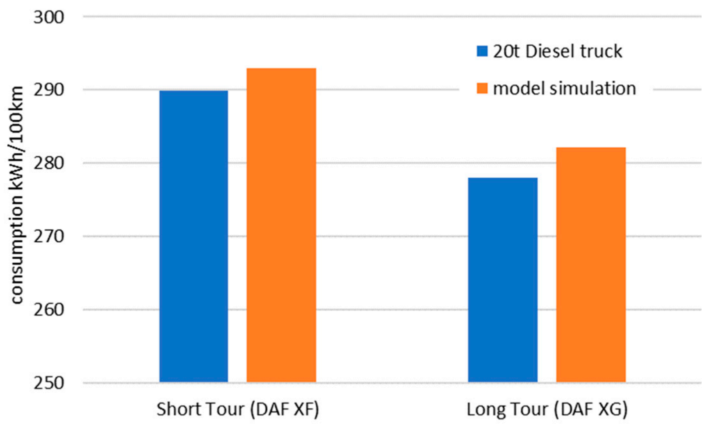


Figure 8. A priori simulated and measured consumption of ICEV trucks on the two reference tours.

3.2. BEV/FCEV Truck Data

In our model, the entire drivetrain (transmission, motor, inverter, battery, fuel cell, tank) can be exchanged between BETs, FCETs, and ICETs much more easily than would be possible experimentally. Of course, drive-technology-specific features have been taken into account. We have paid particular attention to the different weights of the drive components. As in real life, different vehicles were used in the model for the two tours under investigation (Table 10). This was mainly due to the distance of the tours. It was precisely this difference, with its effects on the drive and energy storage, that we paid particular attention to. The data for the diesel trucks used can be found in Table 3.

Table 10. BET/FCET drive data (referring to 2030 values of Table 7; see Tables S1 and S2 of [41]).

Drive Technology	Parameter	Short Tour		Long Tour	
		BET	FCET	BET	FCET
Electric motor	Rated power (kW)	450	450	450	450
	Rated torque (Nm)	1,074	1,074	1,074	1,074
	Max. efficiency	95%	95%	95%	95%
Inverter	Rated power (kW)	700	500	700	500
Battery	Rated capacity (kWh)	600	66	900	66
	Rated voltage (V)	400	400	400	400
	Rated dis-/charging power (kW)	735	500	735	500
	Weight (kg)	2,000	220	3,000	220
Fuel cell	Rated power (kW)	-	396	-	396
	FC weight (kg)	-	400	-	400
H_2 tank	Tank pressure (bar)	-	700	-	700
	Fuel weight (kg)	-	35	-	40
	Tank weight, empty (kg)	-	250	-	250
	Tank weight, fully loaded (kg)	-	285	-	290

As can be seen from Table 10, the main differences resulting from the tour distance are in the battery and tank capacities. The rest of the drivetrain could be kept the same as the payloads differed only slightly. Particular attention should be paid to the drive-technology-specific differences in battery sizes. While the BET battery must store the amount of energy required for the entire journey, the FCET battery can be dimensioned significantly smaller. This is because the main energy store in the FCET is the hydrogen tank. The battery only has to supply the engine with power for a short time. Due to the dominance of highway driving, little more than 10% of the BET battery capacity is sufficient for this purpose. Due to the high energy density, the hydrogen tanks vary only slightly on the different tours.

As expected, the ICET-CNG weighs the least, as the combustion engine only requires the CNG tank for energy storage. The CNG stored there under high pressure has a low weight with a high energy density. The FCET contains most of the drive components, including the gearbox, motor, inverter, battery, fuel cell and hydrogen tank; therefore, it has a somewhat higher weight. However, the battery is significantly smaller compared to the BET. In total, the FCET is heavier by about 1 t than the ICET-CNG, but lighter by 2 t than the BET. Figure 9 illustrates that the additional weight of the BET is exclusively due to the battery, which weighs 3 t for the long reference tour with a capacity of 900 kWh (see Table 10). This significant difference in weight has a negative effect on the BET's energy consumption, especially in hilly terrain.

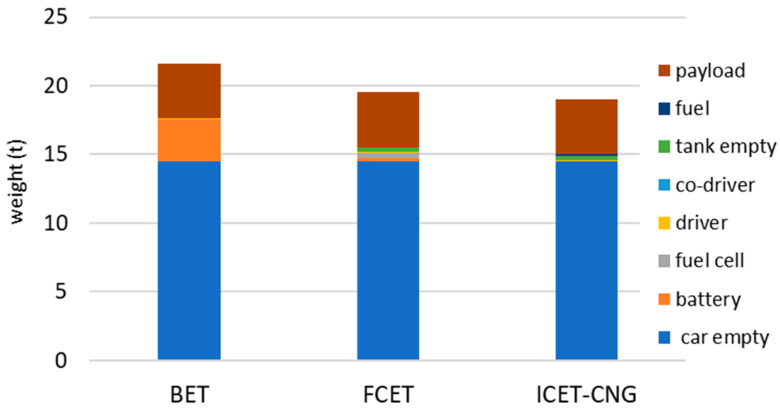
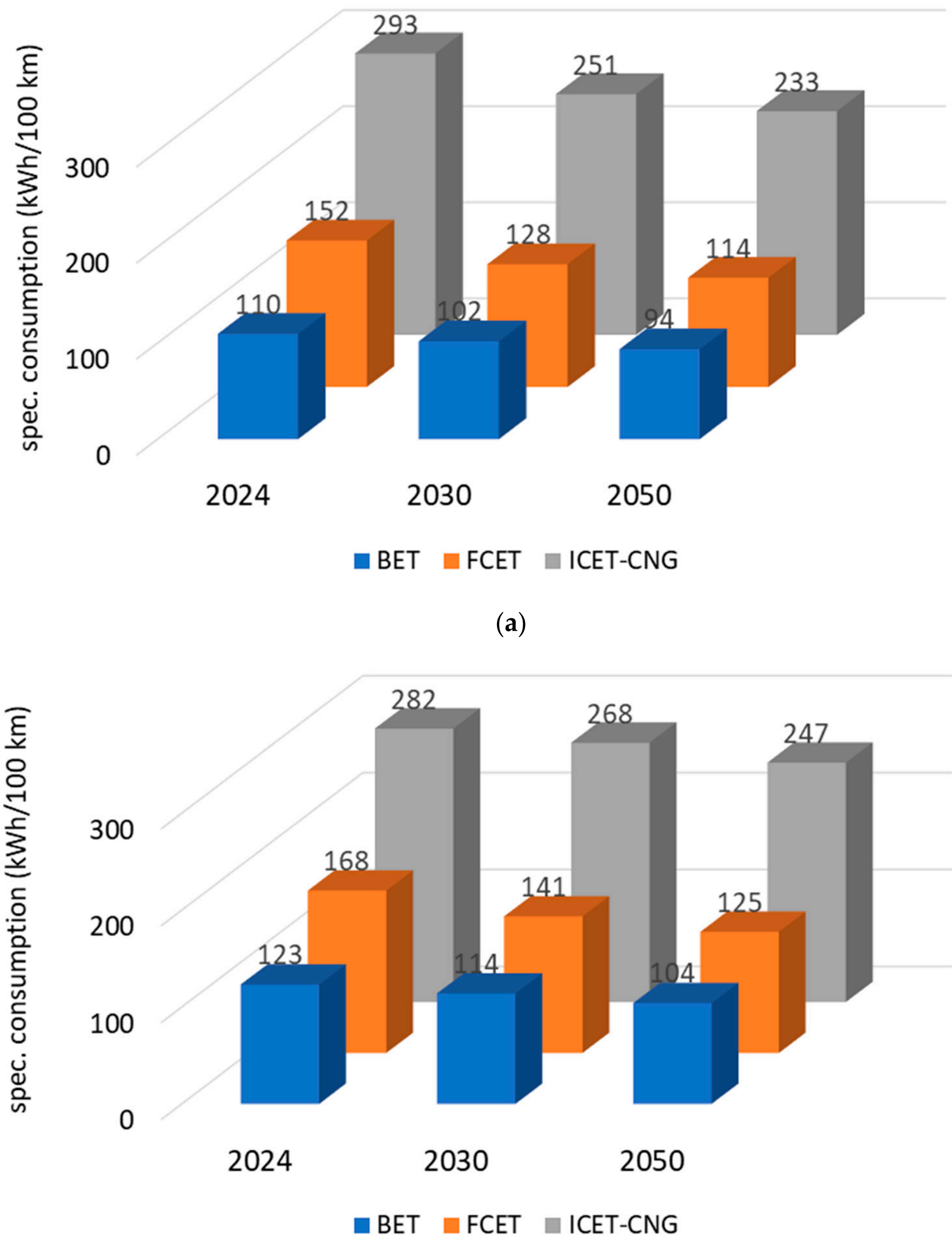


Figure 9. Weight shares of the various truck components on long tour (referring to 2030 values of Table 7; for more details, see Tables S3 and S4 of [41]).

3.3. *Specific Consumption of BETs, FCETs, and ICETs-CNG*

The truck and tour data described in Sections 2.4, 2.5, 3.1 and 3.2 were used to determine the consumption of BETs and FCETs at the current state of the art. Together with the expected technology developments from Section 2.6, this allowed model-based predictions for the medium-term period up to 2030 and the long-term period up to 2050. We predicted technological progress not only for the new drive technologies BET and FCET but also for the ICET-CNG. Although the latter is considerably more advanced in its development than BETs and FCETs, there is further potential for sustainable improvement, as evidenced by the recent progress made by DAF with its XG generation (see Table 9).

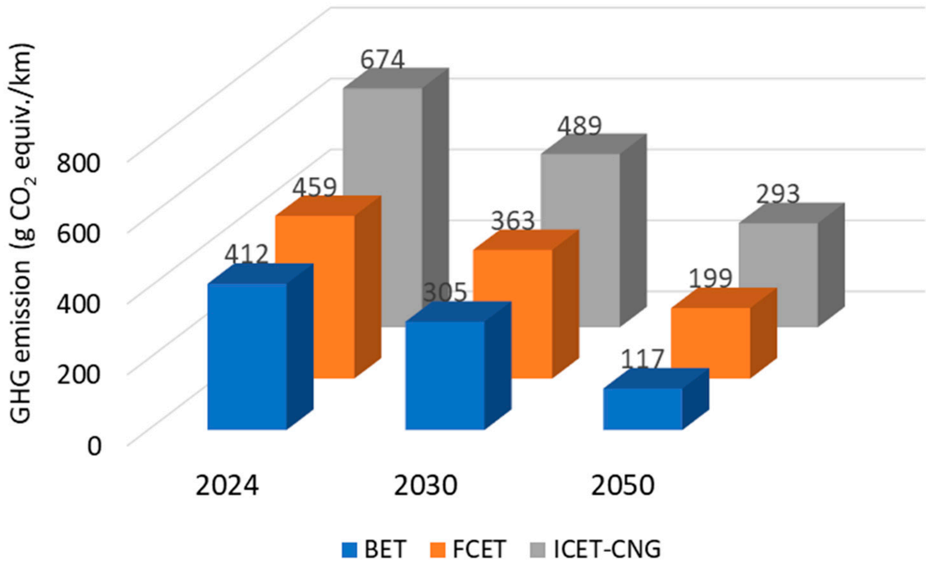
The results are summarized in Figures 10 and 11. Specific consumption figures are usually given in l/100 km for liquid fuels, in kg/100 km for gaseous fuels, and in kWh/100 km for electric drives. For the sake of comparability, we have converted the various dimensions to kWh/100 km (H_2: 33.30 kWh/kg, CNG: 13.36 kWh/kg). The great savings potential in the transition from ICET-CNG_{2024} to the new BET and FCET technologies is evident. The BET_{2050} and the $FCET_{2050}$ will only consume 34.4% and 41.6%, respectively, of the energy required by the ICET-CNG_{2024}. The higher energy requirement of the FCET compared to the BET is due to a longer drive train. However, at 17%, the difference between BET_{2050} and $FCET_{2050}$ is less than the underlying efficiency loss of the fuel cell ($\eta^{FC}{}_{2050}$ = 75%, as outlined in Figure 7 of [31]). This is caused by the significantly higher weight of the BET (see Table 10 and Figure 9). The resulting additional consumption is caused by the fact that acceleration and gravitational losses increase with mass.



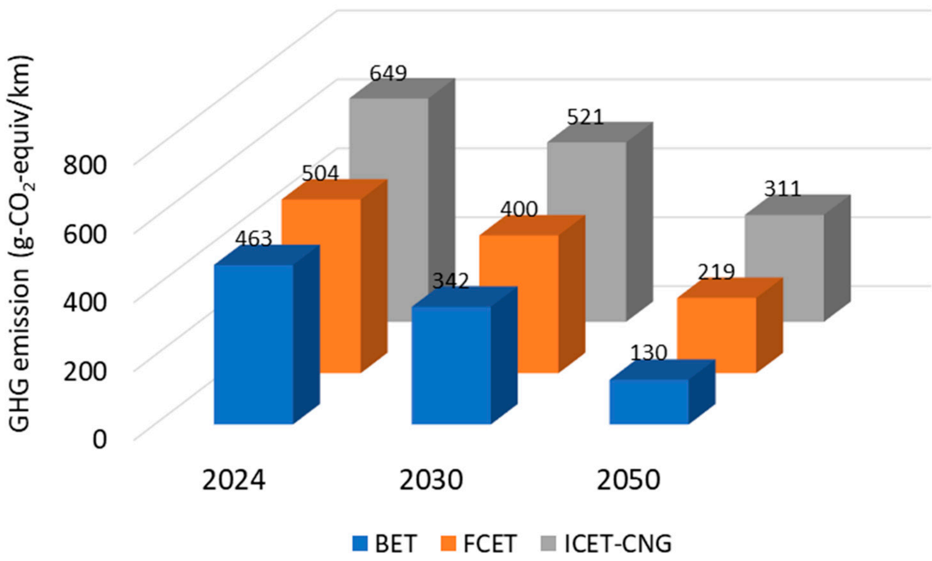
(**a**)

(**b**)

Figure 10. Specific consumption of a 20-ton truck. (**a**) Short tour. (**b**) Long tour.



(**a**)



(**b**)

Figure 11. Specific GHG emissions of a 20-ton truck. (**a**) Short tour. (**b**) Long tour.

3.4. GHG Emissions of BETs, FCETs, and ICETs-CNG

The calculated predictions for GHG emissions (Figure 11) produce results comparable to the specific consumption (Figure 10). This may not seem surprising, but in addition to the specific consumption of the vehicles, the calculation of GHG emissions also includes the emission factors of the various energy generation paths. No distinction is made between fossil, renewable, and other generation paths for long-term (2050) prediction. Instead, the values used are based on the assumption of an expected generation mix that will consist primarily, but not exclusively, of renewable energies (Section 3.4 of [31]).

As indicated in Figure 11, the use of BET and FCET drive technologies in day-to-day forwarding operations will save a high proportion of today's GHG emissions. The BET_{2050} and $FCET_{2050}$ will emit only 18.7% and 27.5%, respectively, of the GHG emissions of the $ICET\text{-}CNG_{2024}$. On the one hand, these significant reductions are due to the lower specific consumption of the trucks (Figure 10). On the other hand, the improved energy generation structures in 2050 will have a reinforcing effect. In Germany, the emission factor of electricity is expected to be reduced from 376 (2024) to 125 (2050) g/kWh, and the expected reduction for hydrogen is from 301 (2024) to 175 (2050) g/kWh (Table 8). The significantly greater improvement on the electricity side compared to hydrogen will increase the gap between BET_{2050} and $FCET_{2050}$:

$$gap(specific\ consumption) = 1 - \left(\frac{specific\ consumption(BET2050)}{specific\ consumption\ (FCET2050)} \right) \quad (1)$$

$$gap(GHG\ emission) = 1 - \left(\frac{GHG\ emission(BET2050)}{GHG\ emission(FCET2050)} \right) \quad (2)$$

Averaged for the two tours, the gap (*specific consumption*) results in 17.2% while the gap (*GHG emission*) is significantly larger at 40.9%—due to the reasons mentioned above (Figures 10 and 11).

3.5. Consumption Shares, Recuperation

Other than an ICE, an electric motor is able to convert the kinetic energy of the vehicle into electricity and thus recharge the battery while driving because it can work not only as a motor but also as a generator. Recuperation reduces fuel consumption and extends the vehicle's range, but it is only generated by the two physical forces of mass inertia and gravity. While air and rolling resistance can only act against the direction of driving, both mass inertia and gravity can also develop effective pushing forces in the direction of driving. The motor/generator partially converts these forward-acting forces into battery charge. The ratio of the battery charge generated to the kinetic energy available in the direction of driving is the recuperation factor. Its magnitude must of course be less than 1. The recuperated energy has a negative sign as it helps to reduce consumption (energy consumption is usually described with a positive sign, as in our work). Recuperation in an FCET is lower than in a BET because of the additional efficiency loss of the fuel cell (Table 11).

Table 11. Recuperation in electric 20-ton trucks (long reference tour, 2024).

Parameter	BET	FCET	Dimension
Recuperation factor	66.8	64.9	%
Total recuperated energy	−49.70	−38.49	kWh
Recuperated energy by gravity	−38.61	−29.88	kWh
Recuperated energy by mass inertia	−11.09	−8.61	kWh

Figure 12 shows that at about 45%, the dominant share of consumption comes from air resistance. The reasons are the less than aerodynamic shape of trucks and the high proportion of motorway driving. On the long tour, the truck drives more than half of the total time at speeds between 80 and 90 km/h. This also explains the low consumption share of mass inertia: the truck hardly accelerates throughout the journey.

In the case of the FCET, the consumption shares of gravity and mass inertia are lower than in the case of the ICET-CNG, although the mass of the FCET is greater. It is recuperation that reduces these consumption shares. This important aspect can solely be studied by simulation as road experiments will only provide integral consumption values. Similar remarks apply to the BET, except that the heavy battery of the BET almost completely compensates for the advantage of recuperation compared to the ICET-CNG.

Details of simulation results can be found in [41].

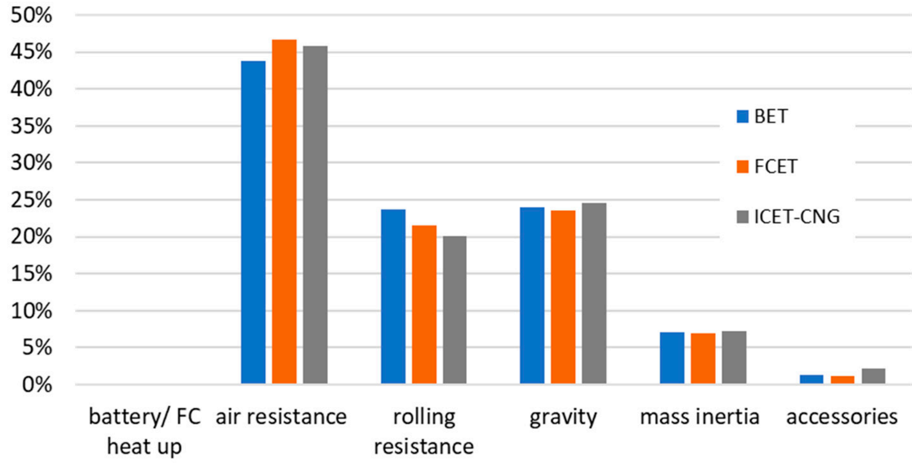


Figure 12. Consumption shares in 20-ton trucks (long tour, 2024) (for details, see Figure S6 of [41]).

3.6. Discussion

In our earlier work [5,31], we were able to verify the basic technological assumptions of our model for passenger cars and light trucks. The excellent agreement of the simulation results for ICET trucks with observed real-world data (Figure 8) means that the model extension to medium-duty trucks up to a total weight of 25 t can now also be regarded as verified. We emphasize that we did not optimize any one of the many parameters a posteriori to improve the agreement between simulation and measurement irrespective of physics and causality. The model does not perform a functional approximation but is based on physics and the technological state of the art and all of its parameters are given theoretically known, measured or physically plausible values prior to simulation. On this basis, we were now able to carry out simulations with BETs and FCETs and make physically objective predictions for the future up to 2050.

The specific consumption of trucks depends on truck details, specific terrain profiles, climate, etc. ICETs are highly developed with a relatively stable state of the art. The situation is different for BETs and FCETs in that they are in an early phase of development, which is always associated with a highly time-variant state of the art. It was therefore all the more important for us to look for comparisons with other scientific studies that are as up to date as possible and originate from different countries. Table 12 shows such a comparison for truck weights around the weights we analyzed.

Table 12. Comparison of the results with the published literature [13–15,23,29].

Data Source	Year	Truck Gross Weight (t)	Specific Consumption (kWh/100 km)		
			BET	FCET	ICET-CNG
This work—Short Tour, 2024	2024	20	110	152	293
This work—Long Tour, 2024	2024	20	123	168	282
Mareev et al. [23]	2018	40	123–194	-	-
Earl et al. [14]	2018	40	115–144	-	220–330
Z. Mu et al. [29]	2024	16–49	45–125	65–180	-
Ledna et al. [15]	2022	>13	140	210	300
Phadke et al. [13]	2021	36	131	-	-

Basically, taking into account differences in weight, application, and year, the values in the literature correspond well with our results. This applies to all three vehicle types analyzed (BET, FCET, and ICET-CNG). This consistency represents comprehensive verification of our truck model. The model confirmation for passenger vehicles and light trucks by [31] has now been extended to medium freight transportation and trucks with a total weight of up to 25 t.

As shown in Table 12, the largest deviation between our own and other results occur for Ref. [29], which covers a broad weight range of trucks in the Chinese market. The consumption figures stated in [29] are otherwise known from light trucks in regional delivery. As light trucks make up a substantial fraction in Chinese traffic, it can be assumed that lighter vehicles with a total weight below 16 t were included in a source not further specified in Section 2.3.2 of [29].

The consumption range given by Mareev et al. [23] begins at values we also found and extends to much greater values. Obviously, the effective weight of the trucks considered by [23] exceeded our values, reaching up to 40 t (full load).

As the CO_2 factors for electricity vary significantly from country to country, there are limited relevant data for a scientific comparison of GHG emissions. Any further comparison of GHG emissions from FCETs involves large uncertainties as the hydrogen production chains are not yet established. We therefore restrict our attention to Earl et al. [14]. Figure 3 of this work outlines ICET tank-to-wheel GHG emission values of 600 to 850 g CO_2 equiv./km. This correlates very well with our results of 649 and 673 g CO_2 equiv./km. The emissions of the new DAF XG trucks thus correspond closely to the best-in-class values of [14]. Unfortunately, Earl et al. only provide well-to-tank values for the BET, which are not comparable with our values. However, as the specific consumption values for BETs and FCETs correlate well, the agreement for GHG emissions is reduced to the question of electricity generation. When generation chains and, thus, emission factors can be compared, it can also be concluded that the GHG emissions match.

4. Conclusions

In conclusion, the BEV truck has the lowest emission and consumption values due to its high drivetrain efficiency, but the high weight of the battery increases consumption, especially in hilly terrains and in the city, and thus limits the driving range. The practicability of recharging the battery further restricts the flexibility of forwarding logistics. These statements apply beyond the specific road freight transport use case examined, while the figures presented below apply to the use case:

In numbers, BET_{2050} will consume a third of the energy of the $ICET_{2024}$ and will emit only a fifth of the GHG of the $ICET_{2024}$.

The FCET consumes 20% more energy and emits 30% more GHG than the BET. This is due to the lower efficiency of the longer drivetrain but is partially compensated for by the significantly lower weight of the drive system. If hydrogen becomes available at low cost, forwarding logistics will not lose any flexibility with the FCET compared to the status quo. Due to the high energy density of hydrogen, the FCET has no range limitation. In numbers, $FCET_{2050}$ will consume 60% less energy than the $ICET_{2024}$ and will emit only a third of the GHG of the $ICET_{2024}$.

Due to its low engine efficiency, the ICET has only limited application possibilities in the medium term. A long-term perspective would only be given if the fuel can be produced largely from renewable sources. Thanks to the further development of combustion technology and ecological progress in fuel production, a reduction in GHG emissions to half by 2050 is also possible for the ICET. In numbers, $ICET_{2050}$ will consume 20% less energy than $ICET_{2024}$ and will emit only half of the GHG of $ICET_{2024}$.

The determining consumption factors in long-distance transport are, in order, air resistance, gravity, and rolling resistance. Considerable efforts are needed to reduce fuel consumption in the medium term, particularly with regard to air resistance. By means of recuperation, the range can be extended by 3–7% on the tours investigated.

The results of our work confirm that the transformation of medium and heavy road freight transport to new drive technologies represents a far greater challenge than is already the case for passenger vehicles and small trucks. Many questions relating to BEV or FCEV trucks cannot yet be answered sufficiently well:

1. What does the infrastructure at the forwarder's location need to look like to enable economical transportation?
2. What does the infrastructure have to look like on the road and at forwarder's customers to enable economical transportation?
3. Can hydrogen be made available cheaply enough to enable economical transportation?
4. When will FCETs be offered by several internationally active manufacturers?

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14209535/s1, Supplementary materials PDF.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

ADAC	Allgemeiner Deutscher Automobil-Club, Europe's largest automobile club
BET	Battery electric truck
BEV	Battery electric vehicle
CNG	Compressed natural gas
DHL	German forwarding company
FC	Fuel cell
FCET	H_2 fuel cell electric truck
FCEV	H_2 fuel cell electric vehicle
GHG	Greenhouse gas
GPS	Global positioning system
H_2	Hydrogen
ICET	Internal combustion engine truck
ICET-CNG	Internal combustion engine truck running on CNG
ICEV	Internal combustion engine vehicle
PV	Photovoltaic
TCO	Total cost of ownership
UPS	American forwarding company
UTM	Universal Transverse Mercator, a global coordinate system
WLTP	Worldwide harmonised light-duty vehicles test procedure

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