Alternative drive trains and fuels in road freight transport – recommendations for action in Germany

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INTRODUCTION AND MOTIVATION

This paper develops theses and recommendations for action on climate protection in road freight transport in Germany. Scientists from the Fraunhofer ISI, Oeko-Institut and Institute for Energy and Environmental Research (ifeu) have worked on various research projects on this topic in the last few years. The aim of this work is to constructively present the cumulative knowledge of project partners. This paper is primarily addressing policy makers and is intended to stimulate further discussion on this important sub-topic of climate policy.

1 CHALLENGES

Greenhouse gas emissions from long-distance freight transport are increasing continuously - reversing this trend is a particular challenge.

According to the German government's 2050 climate protection plan, CO_2 emissions from the transport sector are set to decrease by 40 to 42 percent by 2030 compared to 1990 levels, to 95-98 million tonnes of CO_2/a.[1] In view of the Paris targets, an almost complete reduction in CO_2 emissions from transport is necessary by 2050. However, the current trend points in a different direction: in recent years, CO_2 emissions from transport have risen again due to an increase in mileage, amounting to more than 170 million t CO_2/a in 2017.[2] Of this, approx. 40 million t CO_2/a are caused by heavy commercial vehicles (trucks >3.5 t gross vehicle weight) – with an upward trend.[3]

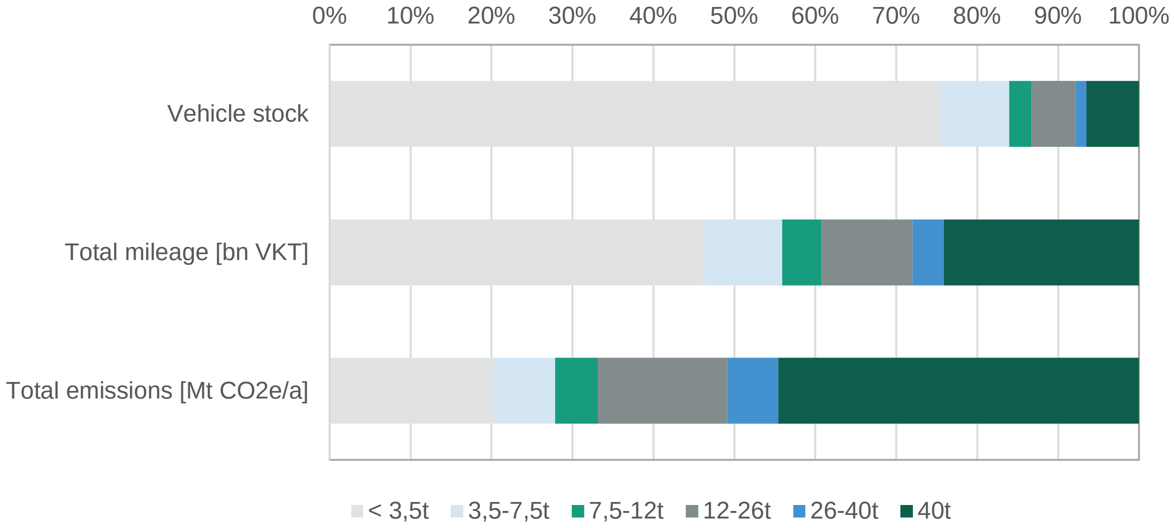

Figure 1: Vehicle stock, total mileage and CO_2 emissions of commercial vehicles in Germany in 2016 differentiated by gross vehicle weight (Source: Timmerberg et al. 2018).

The necessary contribution of heavy goods vehicles (trucks) to reducing CO_2 emissions and thus to achieving Germany's climate protection targets is of crucial importance. Today's truck traffic accounts for 73 % of the transport mileage in German freight traffic,

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[1] BMUB 2016

[2] UBA; BMU 2018

[3] Zimmer et al. 2016

with a further increase expected in the future.[4] Without the improved utilisation and efficiency of these vehicles, CO_2 emissions from road freight transport will increase by a further 10 million tonnes by 2030. This would make reaching the climate protection target for transport nearly unattainable.[5]

A further shift from road to rail is important, yet rail capacities are limited.

Transport reduction and a shift from road to rail are important options for action, as they help to address the challenge and achieve the stated objectives. Rail remains the preferred option for necessary transport. Today's freight transport in Germany is already largely electrical and energy-efficient. The German energy transition includes a gradual shift to renewable electricity, which will reduce CO_2 emissions.

Currently, four times as many tonne-kilometres of goods are transported by road as by rail. Several studies have analysed the potential for a shift from road to rail and concluded that even with optimistic assumptions, at least two thirds of freight transport will have to be handled by road in the future.[6]

A significant increase in freight transport by rail would also require considerable investment in new rail networks and the organisation of freight transport. These investments and their effects must be compared to the total costs and investments in CO_2-neutral road freight transport.

The diversity of conceivable drive train alternatives hinders policy decisions by actors in road freight transport.

Electric vehicles (including plug-in hybrid and pure battery electric vehicles) are a technical option for reducing GHG emissions in passenger cars and light commercial vehicles. This is supported by most experts in view of the ongoing development of battery technology – at least in countries with a good electricity distribution infrastructure. In contrast, possible technical solutions for heavy freight transport by road are more controversial, as the high specific energy consumption in particular poses a challenge in terms of range. Four alternative drive or fuel options will therefore be distinguished in the following:

(1) Overhead catenary (OC) hybrid trucks drawing electricity from an overhead line and supplemented by an additional diesel engine or battery for travel aside from the overhead line;
(2) Hydrogen-powered fuel cell (FC) trucks;

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[4] cf. e.g. BMUB 2016b

[5] cf. e.g. BMUB 2016b

[6] SRU 2012, UBA 2016b, Holzhey 2014, Zimmer et al. 2016 and UBA 2016

(3) Purely battery electric (BE) trucks charged at charging stations; and
(4) Conventional combustion engine trucks that run on synthetic fuels from renewable electricity which can be either gaseous (power-to-gas, PtG trucks) or liquid (power-to-liquid, PtL trucks).

Overall, which alternative drive train will prevail in the future remains uncertain. The variety of options makes investments in a certain technology appear risky for both vehicle manufacturers and truck operators. It is further exacerbated by the uncertain expansion of the respective supply infrastructure. With this paper, we intend to contribute to reducing this uncertainty of action and to advance decarbonisation in road freight transport.

2 COMPARISON OF ALTERNATIVE POWERTRAINS AND FUELS

Various technical options compete with each other.

Nearly 100 % of the current truck fleet in Germany operates on conventional diesel engines, as they meet many user requirements for trucks: comparatively low fuel costs and investments, high engine performance, flexibility, range and reliability. Depending on the application, some requirements outweigh others: In long-haul transport, fuel costs dominate, while flexibility plays a major role in local transport logistics – as does increasing local emission-free delivery in cities.

Some studies have discussed alternative fuels (e-fuels and biofuels as well as natural gas or synthetic gases) for use in adapted combustion engines.[7] These options have the advantage of using existing drive technology and supply infrastructure. The production of synthetic e-fuels is comparatively less efficient than the direct use of electricity; they currently have high production costs and they are not locally emission-free. The potential of biofuels is also limited. Furthermore, natural gas drive trains (CNG or LNG) are currently being discussed and in some cases tested, primarily for energy-strategic reasons. However, natural gas faces the same climate protection challenges as liquid fuels and is therefore not considered separately here.

Recent studies are thus increasingly focusing on electrified alternative drive trains such as battery electric, fuel cell or overhead catenary drive trains for heavy commercial vehicles.[8] While a purely battery electric drive offers high energy efficiency, it is currently more suitable for shorter distances due to its low energy density and recharging time of the battery.[9] Fuel cell drives using liquefied hydrogen offer longer ranges and faster refuelling, but their energy efficiency is poor due to conversion losses, which leads to high costs, and the concept for a nationwide infrastructure is unclear.[10] Catenary drive trains are a proven technology from rail transport and offer high efficiencies. However, they carry with them a high market entry barrier: infrastructure development. Table 1 depicts these aspects in a comparative way.

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[7] see e.g. Bahn et al. 2013, Askin et al. 2015

[8] Mulholland et al. 2018, Talebian et al. 2018, Plötz et al. 2018, Kühnel et al. 2018.

[9] Mulholland et al. 2018

[10] Gnann et al. 2017

Table 1: Overview of alternative powertrains and fuels for trucks

	Fuel cell (FC)	**Battery electric (BE)**	**Overhead catenary (OC)**	**Synthetic fuels (PtG /PtL)**
Motors and technology	Electric motor and fuel cell with hydrogen as energy storage	Electric motor and battery as energy storage	Electric motor and power from overhead lines, if necessary with battery as energy storage or additional combustion engine	Internal combustion engine and pressurized gas or liquid tank as energy storage device
Conversion steps Fuel production from electricity	Conversion to hydrogen (electrolysis)	Direct Use	Direct Use	Conversion to hydrogen (electrolysis) and further to carbonaceous fuel
Efficiency today with the use of renewable electricity	Circa	Circa	Circa	Circa
tank-to-wheel	40 – 50 %	90 %	90 %	35 – 40 %
well-to-tank	60 – 70 %	90 %	90 %	50 – 60 %
well-to-wheel	25 – 35 %	80 %	80 %	20 – 25 %
Technological readiness level of vehicles	Several test projects (TRL 6-7)[11]	First commercially available vehicles (TRL 8)[11]	Several test projects (TRL 6-7)[11]	Conventional vehicles
Key challenges	Infrastructure development and increased power requirements due to high conversion losses, cost reduction in fuel production	Limited range, long charging time and payload losses	Infrastructure development, acceptance, integration in logistics processes	Strongly increased power demand due to highest conversion losses, cost reduction in vehicle and fuel production

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[11] TRL = Technological Readiness Level with steps from TRL 1 (basic principles observed) to TRL 9 (actual system proven in operational environment), cf. EU 2014.

Electric drives have the crucial advantage of low operating costs for trucks.

The competitiveness of companies in the logistics market is largely determined by transport costs. A central requirement for the vehicles used and thus for the market success of a drive train technology are therefore competitive total costs for a typical period of use of the vehicle in long-distance transport. In view of the high annual mileage of trucks in long-distance freight transport, the operating costs are much more relevant for the total costs of ownership (TCO) than for passenger cars. Several studies (see Figure 2) have shown that drive trains using direct electricity (OC trucks and BE trucks) in particular can already achieve overall costs similar to efficient diesel trucks in long-distance road haulage in the short term (if technological development is continued and even if the fiscal framework remains unchanged (e.g. taxes, levies, tolls)). The higher capital expenditure is offset by lower operating costs. Significantly higher overall costs, on the other hand, are still associated with the use of fuel cell trucks or synthetic fuels in internal combustion engine trucks, as the fuel costs per kilometre are higher here.

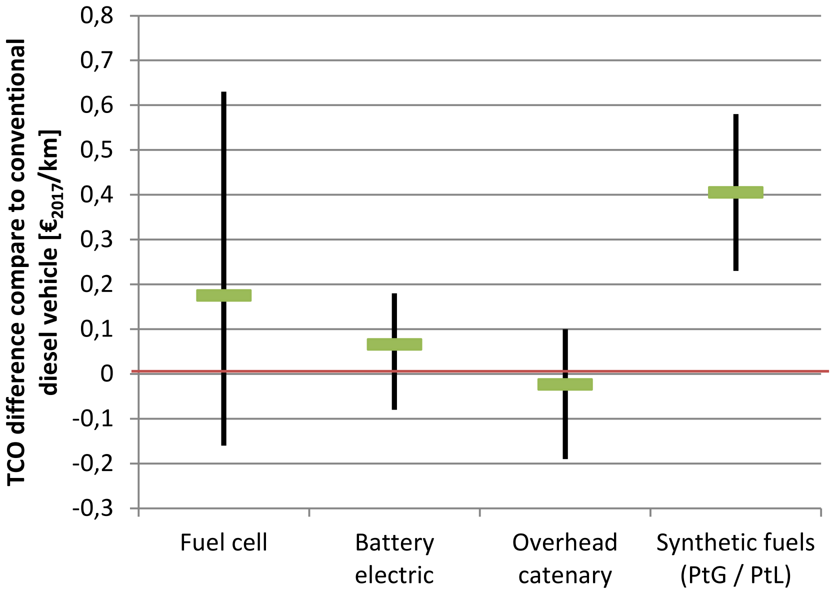

Figure 2: Variation in TCO of different alternative drives / fuel options relative to fossil diesel vehicles in the period 2020 – 2030 (mean value (in green) and bandwidth between different studies).[12]

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[12] Sources: Fulton et al. 2015, Moultak et al. 2017, Wietschel et al. 2017, Kühnel et al. 2018, ifeu 2018, Miyasato et al. 2012, den Boer et al. 2013, PtL-Cost from Maier et al. 2018, km- Cost calculated using truck TCO model from ifeu 2018; Notes: Costs have been transferred in $€_{2017}$; the period and time under consideration vary between 2020 and 2030 depending on the source; both short and long-haul trucks are considered.

In some cases, there are large variations both in the assumptions regarding future component costs (in particular for fuel cells) and in framework conditions (e.g. energy price development). The variation in total cost of ownership (TCO) of the individual technologies caused by these uncertainties is of a similar magnitude to the TCO differences between different technologies. Particularly relevant for economic efficiency are the mileage-related cost components. Already minor changes in e.g. energy prices and tolls can shift the comparative total costs of the technologies. The economic efficiency of alternative drive systems compared to established diesel technology could increase if the lower emissions of greenhouse gases and air pollutants were incentivised in the pricing of energy and infrastructure use – e.g. by incorporating a CO_2 component in energy taxation or infrastructure levies. Assigning infrastructure costs to the few vehicles with alternative drives during the market ramp-up phase would make achieving cost parity more difficult due to the initially low level of infrastructure utilisation.[13]

Alternative drive trains require early infrastructure investment.

While a comprehensive supply network exists for diesel fuel, the drive train and fuel alternatives – with the exception of synthetic fuels – require the development of a separate energy supply infrastructure. This ranges from a distribution and refuelling infrastructure for hydrogen in the case of fuel cell trucks, to a network of charging points for battery electric trucks and electrified highways for long-distance overhead catenary trucks.

The challenge in the early market phase is that a universal service network is a prerequisite for alternative vehicles to become attractive for users. Given the small market volume, however, the construction and operation of the infrastructure is unlikely to be profitable during this period. Nevertheless, in road freight transport – more so than in passenger transport – there is likely to be the possibility of creating an attractive supply network for initial applications at an early stage with a relatively low network density or for selected corridors (e.g. for regional or commuter traffic and on highly frequented corridors).

A current study analyses the infrastructure costs for the initial construction and expansion of a network in Germany to supply about 5,000 and 40,000 long-haul trucks respectively for the energy supply variants under consideration.[14] These range from €280 million for an initial network of hydrogen filling stations (with decentralised production) to €850 million for a two-sided electrification of 500 km of highways with overhead lines. According to this estimate, the investments for the entire initial and expanded network range between €2.3 billion (hydrogen filling stations) and €5.1 billion (2,000 km of overhead lines).

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[13] see Kühnel et al. 2018

[14] Kühnel et al. 2018, cf. also Wietschel et al. 2017 and Fulton et al. 2018

Table 2: Estimation of infrastructure investments for two network expansion stages (initial network / expansion network: supply of max. 5,000 / 40,000 trucks).[15]

	Hydrogen filling stations	Charging station network	Overhead line (network length)
initial network	€290 mn.	€510 mn.	€850 mn. (500 km)
extension network	€2,300 mn.	€3,700 mn.	€5,100 mn. (2,000 km[16])

When assessing the difference in costs between infrastructures, it should be noted that the total cost of ownership also differs significantly among the different drives. For overhead catenary trucks, for example, Figure 2 shows TCO to be about 20 €ct/km lower than for fuel cell trucks. For the expansion scenario mentioned here, this would correspond to savings in operation of up to €600 million per year, compensating for the higher infrastructure costs of the overhead line network after about five years.

Overall, the cost estimate is subject to uncertainties as it is strongly dependent on assumptions regarding the use of the infrastructure and the subsequent infrastructure design. Moreover, the actual implementation costs can only be roughly estimated on the basis of the current state of knowledge. Initial experience with the actual costs (planning, execution and operation) of an overhead line infrastructure is currently being gathered in a series of field trials.

Catenary trucks have advantages in terms of energy economy, as the electricity requirement is comparatively low and is distributed more evenly over the route network.

For the energy sector, the absolute quantities of electricity, the generation capacity and performance required and, if necessary, storage are relevant issues for the comparison of alternative drive trains in road freight transport.

The absolute electricity demand for overhead catenary trucks and battery electric trucks is lower than for other alternative fuels.[17] Moreover, the necessary additional expansion of

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[15] Figures from Kühnel et al. 2018

[16] The costs for the expansion network not only include the additional kilometres, but also a higher specific capacity of the infrastructure to supply the 40,000 trucks mentioned above.

[17] If 30 % OC trucks with a 50 % share of electric driving in Germany were to penetrate the market in 2030, around 8 TWh of electricity per year would be required, and all trucks with more than 12 t GVW would have to be replaced with just under 36 TWh/a (30 % BE trucks required 16 TWh). This would be a small amount of electricity compared to the German gross electricity production of 655 TWh in 2017 (AGEB 2018). A complete conversion to hydrogen would require 72 TWh/a, and 104 TWh/a for e-Diesel.

renewable energies is quite realistic and below the capacities currently available.[18] The necessary generation capacities for a climate-neutral energy supply would be about twice as high for the hydrogen option (FC trucks) and about three times as high for synthetic liquid fuels such as e-Diesel (PtL trucks) as for overhead catenary trucks and battery electric trucks.

The load of overhead catenary trucks is constantly demanded while driving and could lead to bottlenecks in local network. However, first evaluations show that the grid load is rather low compared to the increasing energy demand and could only become a problem in rural, sparsely populated areas.[19] However, if renewable energies are expanded accordingly, OC trucks could at the same time lead to grid relief. The fluctuation of renewable energies could, however, make storage necessary, which would be easier with other alternative fuels. PtL trucks and FC trucks also require the appropriate generation facilities, but these could be better controlled with appropriate storage facilities and thus also represent an important flexibility option. Pure battery-electric vehicles need similar amounts of electricity to OC trucks, but locally require much higher capacities for recharging (e.g. at rest stops during breaks). Thus a much higher local grid load is to be expected than with OC trucks.

It is important to mention that, according to the current state of science, electricity-based fuels (from hydrogen to e-Diesel) must be used in other modes of transport (air and sea transport) for climate-neutral operation in the future because limited space and weight restrictions largely rule out the use of electric drive trains.

All alternative technologies offer opportunities for domestic value creation - there are differences in dependence on energy imports.

Achieving climate protection targets in the transport sector also means a comprehensive transformation in the truck sector. There are already activities worldwide in this area, whereby Germany can play an important role in the transformation due to its strong market share in the truck sector. To this end, it is important to demonstrate the use and function of the technologies in Germany.

With regard to the technology for overhead catenary trucks, German rail technology companies have extensive experience and are drivers in the development of infrastructure technology. German truck manufacturers and their subsidiaries can play an important role in the further development of trucks, as they are already involved in the pilot projects.

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[18] Assuming an average of 1,000 full load hours, systems with a peak output of approx. 36 GW would have to be installed in order to generate 36 TWh of renewable electricity from photovoltaics. For onshore wind turbines with 2,000 full load hours, this would mean 18 MW of installed capacity, for offshore turbines with 4,000 full load hours, approx. 9 MW (BMWi 2017). Here, too, a comparison with the currently installed capacity of PV (41 GW), wind onshore (46 GW) and wind offshore (4 GW) demonstrates feasibility in the long term.

[19] Wietschel et al. 2017

Germany also has a high level of expertise in battery technology, especially at universities. The establishment of production capacities for battery cells in Germany is currently being discussed, which could also enable expanded production expertise. German plants could be also potentially constructed for the development of conversion technologies for electrolysis, methanisation, methanol synthesis or Fischer-Tropsch synthesis. Lastly, Germany will remain dependent on imports of liquid fuels from renewable electricity, as the costs of nationally-produced synthetic fuels clearly exceed those of imported fuels (Timmerberg et al. 2018). Even with cost parity, renewable energy generation capacities in Germany are insufficient to decarbonise air and sea transport in addition to trucks.

For all industries and technologies, however, it is important not to miss the moment of opportunity, as was the case in the battery sector. Early testing and participation in demonstration projects are vital.

Conclusion: Electric drives have clear advantages, above all because of their high energy efficiency.

The summary of relevant evaluation criteria of the considered alternative drive options (Table 3) shows some clear advantages of the electric drive systems. In principle, their high efficiency enables a domestic supply of renewable energy. In principle, overhead line and charging station infrastructure can be used in combination by electric vehicles, reducing the risk of stranded investments. In terms of energy economy, the electricity and power quantities for overhead catenary trucks appear to be locally less problematic than for battery electric trucks, whereas flexible load generation offers slight advantages for FC and PtL trucks. With regard to domestic value added, there is potential in all areas, but import dependency will be highest for PtL fuels.

Taking these arguments into account, it is recommended that the development of an initial electricity supply infrastructure (overhead lines and charging points) be given higher priority than other infrastructural measures.

Table 3: Comparison of alternative powertrains and fuels for trucks

	Fuel cell (FC)	**Battery electric (BE)**	**Overhead catenary (OC)**	**Synthetic fuels (PtG /PtL)**
Power requirement for all German tractor units [TWh]	Ca. 70	Ca. 36	Ca. 36	Ca. 105
User costs vs. diesel truck [€/km][20]	-0.15 to 0.6	-0.1 to 0.2	-0.2 to 0.1	0.2 to 0.6
Infrastructure	High investments, prefinancing necessary	High investments, prefinancing necessary	Very high investments, prefinancing necessary	No high investments, existing infrastructure available
Domestic value added	Generation and distribution plants	Electric motor, power electronics	Infrastructure, pantograph and drive system	Internal combustion engine and generation plants
Import dependency	Low	For battery cells	Low	Import of fuels

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[20] see Figure 2 and explanations there

3 CONCLUSIONS AND RECOMMENDATIONS FOR ACTION

The switch to alternative drives requires political action today.

Road freight transport performance has increased steadily in the past and further growth is forecasted, even with a further shift to rail transport. The pressure to act and the challenge for decarbonisation in freight transport are correspondingly high. The necessary, far-reaching reduction of greenhouse gas emissions requires alternative drive train and fuel options. Taking decision-making and planning into account, a time horizon of several years to decades is to be expected for a far-reaching change in the energy supply in road freight transport.[21]

Uncertainties remain regarding the development of alternative technologies, and a significant improvement in the decision-making basis is not to be expected in the coming years. A technological "panacea" will not exist in the next years. However, a comparison of drive trains shows that the direct use of electricity has clear macroeconomic advantages. On the other hand, synergies and possible combinations of alternative technologies are also possible.

The market entry of alternative technologies requires decisive government action. On the one hand, general incentives for greenhouse gas reductions such as a CO_2-based truck toll or the introduction of CO_2 standards for road freight transport are necessary. At the same time, technology-specific measures such as the development of infrastructure and commercialisation should also be tackled. Long-term infrastructure planning must be transparently established ("infrastructure development plan"). Only then, clear market incentives and planning security can be given for future investments in low-CO_2 technologies.

Infrastructure development can be carried out at limited cost, but must be prefinanced by the state.

The development of the necessary energy supply infrastructure is crucial for the advancement of competitive drive alternatives in heavy road freight transport. As other examples show, the development of a new supply network that competes with established technologies and only generates significant benefits with significant expansion cannot be initiated by the private sector nor financed by first users.[22] In the long term, however, in-

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[21] cf. Grubler 1990

[22] cf. e.g. Yeh 2008 for alternative fuel infrastructures

frastructure costs can be borne by users, as they are low compared to energy and capital costs and of secondary importance for users.

At the same time, long-distance freight transport is concentrated very strongly on corridors, so that a large number of vehicles can access a core supply network and high capacity utilisation can be achieved early on. Government action in initiating infrastructure expansion and assuming investment risks in the early market phase is therefore of central importance. The total investment in a basic supply network is estimated at €2.3 – 5.1 billion[23], depending on the drive system. This lies within the range of the current annual revenue from truck tolls in Germany.

Large demonstration projects help to gain practical experience and create acceptance.

The introduction of new drives and fuels in heavy road freight transport can only succeed if technical challenges are mastered while gaining the acceptance of relevant actors (logistics companies, users, vehicle and fuel producers). On the political side, there must be agreement at as many levels as possible – at local, state, federal and European level – on the priority of alternative energy supply infrastructure for road freight transport and the unavoidability of a residual risk for investments in this area. Ultimately, local stakeholders, i.e. residents close to overhead lines, petrol stations, fuel production plants or additional renewable energy production facilities, must also be open to a move towards new drives for heavy road freight transport.

Against this background, marketable alternative drive and energy supply options should be put into practice on a larger scale as soon as possible. This can take the form, for example, of field trials in which commercial pilot projects are carried out for which the state guarantees predictable framework conditions over a longer period of time.

The aim should be to develop a long-term strategy for road freight transport. The evaluation of field trials, early international cooperation and coordination with activities in neighbouring countries are important building blocks here.

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[23] for the supply of about 40,000 trucks, see previous section

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