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CHAPTER FIVE

Decarbonization and freight transport planning

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Abstract

This chapter discusses the potential of spatial and urban planning interventions to help decarbonize freight transport activities. Against a background of continuing growth and individualization of demand, decarbonization of freight transport services is a daunting challenge. The pursuit of decarbonization can take place along different strategic lines including reduction of transport demand, a shift between modes of transport, increase of efficiency of vehicle movements, reduction of energy use of vehicles and reduction of the carbon content of energy. Instruments of collective or public freight planning that can support these strategies include land use planning for logistics activities, freight transport demand management, investments in freight transport infrastructure including ITS, and regulatory and financial policies. Based on the literature we explore the above relationships, leading to a simple conceptual framework that links the decarbonization strategies to the instruments of freight

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transport planning. Urgent areas of future work include the design of multi-strategy roadmaps to achieve decarbonization targets, and the assessment of the effectiveness of combined freight planning measures.

1. Introduction

Decarbonization of the freight transport system is a formidable challenge. While the entire transport system is responsible for about 8% of all energy-based emissions worldwide, freight transport is roughly responsible for half of this amount (ITF, 2023). Targets for emission reduction are steep with EU countries agreeing a 90% reduction in emissions between 1990 and 2050 with a 55% reduction until 2030 (ITF, 2023). The hope is that these reductions will help to keep global warming around the IPCC Paris Agreement targets of 1.5 °C but it is not a trivial question as to how these reductions should be achieved. There is no broad agreement between stakeholders of the sector about which measures should be deployed, when, and how. All measures are expected to be costly and disturb the current balance of economics and power in supply chains (Sharmina et al., 2021; Pfoser, 2022; Humphreys & Dumitrescu, 2021; McKinnon, 2018). Traditionally, freight transport has not played a role of importance in urban or spatial planning functions but over the past decades it has become more visible in the sustainability agenda. While it has generally increased its share in transport emissions due to growth of demand, especially in cities, its increasingly fragmented organization has made it more visible to citizens and planners. This has created support for curbing of growth and for constraining the use of public space for freight transport purposes (Haarstad et al., 2024; Bjørgen & Ryghaug, 2022).

This chapter discusses the possible contribution of freight transport planning instruments to help achieve decarbonization targets in freight transport. The term "freight planning" could be interpreted broadly to include private world supply chain planning functions like inventory planning and routing and scheduling. In this chapter, however, we focus on typical public or societal planning functions in relation to freight transport. Clearly, governments have an important role to play, by deploying instruments only available to public institutions to shape the built environment, including open land, streetscapes and built infrastructure. Their instruments can include:

- Investments in land use and infrastructure, including zoning measures to reserve space for freight activities and the actual creation and maintenance of infrastructure;

- Support for freight demand management, through incentives for horizontal collaboration, leading to consolidation of flows;
- Technology-focused regulation and fiscal measures to restrict use of infrastructure to environment-friendly means of transport;
- Information and communication technologies to support collaboration between shippers, receivers and service providers.

Below we explore the relationships between these instruments and the different approaches for decarbonization of freight transport. The chapter is structured as follows. In Section 2, we introduce the general catalogue of measures considered for decarbonization of the freight transport system. Section 3 provides more detail about these strategies and the role of public institutions in their implementation. In Section 4 we discuss the possible contribution of freight transport planning to these measures. Section 5 concludes the chapter with a summary and states implications for research and practice.

2. Decarbonization in freight transport—a strategic perspective

The volume of carbon emitted in the freight transport sector is a product of different factors of social-economic and technological nature. By analogy to the famous Kaya equation (Kaya & Yokoburi, 1997) emissions per mode of transport can be calculated as follows:

$$F_m = T * M_m * U_m * E_m * C_m$$

where:

F_m = Carbon emission per mode [tCO_2].
T = Demand for transport [tonne-km].
M_m = Share of mode m [%].
U_m = Utilization of mode m [vehicle-km/tonne-km].
E_m = Energy use of mode m [J/vehicle-km].
C_m = Carbon intensity of energy source of mode m [tCO_2/J].

This simple model directly shows the five different ways in which freight transport activities can be decarbonized:

- Reducing the demand for transport, by reducing total volumes to be moved, or the distance to be bridged, or both;
- Shifting freight demand to environment-friendly modes of transport;

- Increasing the utilization of transport equipment, to reduce the necessary number of movements;
- Reducing the use of energy per unit of movement, by improving energy efficiency;
- Changing technology to energy carriers with low carbon content.

The framework for decarbonization broadly accepted by stakeholders of the system (see ALICE, 2019), including its underlying measures, follows this list and is pictured in Table 1. Definitions of measures are included in Appendix A to this chapter.

Naturally these measures are all different in terms of feasibility and effectiveness. Notwithstanding, they are all important to achieve final decarbonization targets. Typically, measures that are highly feasible and can be implemented in the short-term, will not have a very strong effect, while the high-impact measures will be more difficult to implement. As short-term measures will have a longer period until the target years ahead (2040, 2050), they may well have an equal impact on the amount of carbon emission saved, that is the use of the remaining carbon budget, as the high-impact measures.

A first qualitative evaluation of effectiveness and feasibility of detailed measures (translated into the expected time to successful deployment) was provided by ALICE (2019) after extensive stakeholder consultations (Table 1). Roughly, one can see the following patterns:

- Some of the measures that are being implemented today show a significant efficiency impact along with carbon emission reduction of the same order.
- The next wave of measures until 2030 requires a logistics re-organization of multiple actors, that is both shippers and carriers, or significant technological investments, or development of entire new markets, or all of the above.
- There seems to be a belief that most of the measures that are needed to make a difference can be implemented successfully by 2030.
- Those measures with a long and not-too-successful history (at least in Europe), such as modal shift to rail and waterways and broad collaboration for asset sharing in the industry, are still considered feasible assuming a scenario of increasing pressure from consumers (preferences), government (taxation) and new technological opportunities (access to data, AI, autonomy).
- The main need for the future seems to be to consolidate and measure the effects of ongoing and near-term measures and to focus on the necessary preconditions to achieve a major next step until 2030 with measures not considered feasible today (Table 2).

Table 1 Decarbonization measures in five categories.

Reduce demand for freight transport	Optimize use of transport modes	Improve utilization of transport means	Improve energy efficiency of transport	Reduce carbon content of energy
Supply chain restructuring	Optimize mode choice	Consolidate loads	Eco-driving	Active modes
Reduce trade distances	Shift to low-emission modes	Shared warehousing	Optimize engines	Electrification
Decentralize stocks	Modularize transport	Modular packaging	Reduce drag and resistance	Biofuels
Slow down consumption	Mix with slow modes	Storage optimization	Optimize fleets	Hydrogen and e-fuels
Dematerialize	Synchromodality	Optimize vehicle loading	Optimize routing	Advanced charging

Own elaboration after McKinnon, A., 2018. Decarbonizing Logistics: Distributing Goods in a Low Carbon World. Kogan Page Publishers; ALICE. 2019. A Framework and Process for the Development of a Roadmap Towards Zero-emission Logistics, ALICE, Brussels.

Table 2 Feasibility and effectiveness of decarbonization measures (ALICE, 2019). Highlights and labels by the author.

GHG Impact		Time to deployment: Today	Time to deployment: Medium term	Time to deployment: Long term (>2030)
	High >20%	• High-capacity vehicles & Duo-trailers • Electric/hybrids urban	• Consumer behaviour (negative?) • Supply chain restructuring • Synchromodality • Battery electric vehicles	• Wind & Solar • Nuclear energy • Electric highway Energy focus
	Medium 10-20%	• Improving back-hauling • Telematics / transport management systems • Slow steaming ships • De-speeding trucks Efficiency focus	• Decentralization of production and stockholding • Localization and nearshoring • 3D printing products • Multimodal optimization • Modal shift (structural) • Open warehouses and networks • Load consolidation and optimization • Modular packaging and boxes • Electric/hybrids long-haul • CNG/LNG, biofuels (air & sea)	• Dematerialization
	Low <10%	• 3D printing spare parts • Increase storage density and energy efficiency • Tires & wheels • Idling reduction • Automatic transmission • Low viscosity lubricants • Oil by-pass filtration • Light-weighting • Fuel management • Fleet maintenance • Re-routing & Re-timing • Eco-driving • Maintenance • Cleaner diesel • CNG/bioLNG • Biofuels (road)	Organization focus • Autonomous trucks on private roads • Platooning and autonomous trains	• Autonomous trucks on public roads
		Today	Medium term	Long term (>2030)
		Time to deployment		

ALICE (2019) also details the required commitment related to individual measures by all stakeholders in the quadruple helix (industry, government, R&D and civil society) and makes recommendations on the process to manage the transition, including:

- Establishment of a reporting and monitoring system, based on accepted reduction targets.
- Implementation and management of action plans.

Collaboration between stakeholders and continuous advocacy is needed for an industry-wide uptake. This process aspect of solutions is relevant, and it aligns well with the growing emphasis on multi-stakeholder processes in freight transport planning (see Chapter 4 of the book). The vast experience with process design in these processes is now permeating the process of alignment on sustainability issues between urban freight system stakeholders (Churchman et al., 2023; Blinge, 2014).

What still appears to be missing is agreement on a roadmap for decarbonization of freight systems. This roadmap would specify which measures are deployed, by whom, when, and under which circumstances, to achieve the system decarbonization targets. Despite the availability of different popularized outlooks and contributions to such a roadmap (e.g. IEA, 2017; IRU, 2017; ALICE, 2019; CSRF, 2020; ITF, 2023), many important elements are missing for these reports to be classified as solid "theories of change" (Dhillon & Vaca, 2018). Possible explanations for this lack of a roadmap are that the freight transport sector has many stakeholders, is fragmented into silos of states and modes of transport and lacks powerful players that can work across these silos.

In summary, there are 5 clear strategies with many promising underlying actions, that need to be deployed together to achieve decarbonization targets. Their operationalization and implementation is a challenge because of the fragmentation of governance in the system across different countries, modes of transport and individual stakeholders. The next section will provide more detail about the underlying measures, and the mechanisms by which their effects would materialize.

3. Decarbonization measures and mechanisms

3.1 Demand reduction

Demand reduction has been addressed in the literature through different dimensions. If we express demand in ton-kilometers, reduction can either take place through the volume, or the distance component. Volumes can be defined more broadly to not just be expressed in weight terms, but also in space (square meters or cubic meters). Reducing freight volume then may include more efficient packaging – as IKEA has practiced for decades with its flatpacks, with important side-benefits in utilization of transport means.

Distance reduction can take place by shortening trade relations (also known as near-sourcing, reshoring or decentralization of inventories, see e.g. Pedroletti & Ciabuschi, 2023; Mukherjee et al., 2023). A note that needs to be made here is that a single trade link is often part of a larger supply chain, and shortening one link may result in other links of the chain becoming longer. Restructuring can be more radical if consumer-level production is moved to the consumer's home with 3D printing, effectively replacing consumer goods movements in the last mile by bulk materials distribution for printing. Substituting physical consumption with digital consumption, actually leading to dematerialization, is the literal interpretation of demand reduction. This is already an autonomous trend as services make up an ever-larger part of our economy and consumers are becoming used to these shifts towards product-service systems (Tukker, 2004). Finally, moving towards a circular economy with, amongst others, more repairs, re-use and re-manufacturing of products, will not just reduce the need for new products. It will also create new flows of materials, new "reverse" flows from used products to materials, and new "forward" flows of regenerated material towards consumer products. The question whether the circular economy will reduce the need for transport has not yet been answered in the literature. At the surface, it seems that raw material flows will be changing from natural sources of mining as an origin, towards urban sources. This may have a volume-expansion effect (more tons) and a distance-shortening effect (less km). How the balance of these will play out in ton-km is yet unclear.

Besides reducing demand in space and volume, one can also think of reducing demand over time. The less we consume per unit of time, the less transport will be needed. Less consumption can also be translated into less often, less new, or less fast, which is probably easier to realize for consumers and can create significant emission savings. Relaxing the demands concerning timing of deliveries can lead to spreading of flows over the day, which reduces flows during peak times (Holguín-Veras et al., 2018), and results in congestion reduction with significant environmental benefits. McKinnon (2016) reviews the literature on so-called logistics "deceleration" practices. These include direct deceleration (slower transport), indirect deceleration (where slower transport is compensated by acceleration of non-transport activities in the chain, which create only mild increases in emissions), and consequential deceleration, as an effect of other strategies such as a shift in modes.

3.2 Mode balance

The mode of transport that is used to move freight is an important determinant of carbon emissions. Large-scale modes like railways and waterways, if well utilized, strongly benefit from scale economies and will consume little energy and produce lower emissions per ton-km. For decades, government has actively pursued the goal of helping the freight sector to move away from road transport, and use rail or waterways instead. Policies have included limiting access for trucks to environmentally sensitive areas like mountain regions, pricing truck transport and subsidizing the construction of intermodal terminals and transport services. The success of these policies has been mixed; the share of road has increased over the decades (Eurostat, 2024; Takman & Gonzalez-Aregall, 2023). Nevertheless, the choice of mode in freight transport has remained one of the most popular topics for freight transport research in a sustainability context (Kaack et al., 2018; Holguín-Veras et al., 2021). Recent research has emphasized that mode choice decisions cannot be taken outside of the context of the supply chain, within which transport processes operate (Dong et al., 2018, Monios & Elbert, 2020). Changing the mode of transport may require new logistics decisions concerning shipment sizes, inventories, distribution channels, and even trading contracts. For many companies, this has proven to be a bridge too far, as these are costly measures, relative to the current mode of operation. As the price of carbon is expected to increase strongly in the future, companies may decide to rethink their operations including the choice of mode. Changes in supply chains will still be needed, where large-scale modes will require a deceleration of flows with larger inventories. Also, for transshipment to work efficiently and for modes to connect optimally, synchronization of supply chains, transport flows and multiple modes across the network is essential—a concept known as synchromodality (Pfoser et al., 2022, Rentschler et al., 2022).

Options to change modes are relatively low for global transport. Both sea and air cargo transport serve very specific markets, where only for niche products (fast fashion, high-value electronics) one can expect shifts under different circumstances (Bartulović et al., 2022). On a local scale, within city limits, alternatives for road transport are being found in cycling and in waterways transport (Browne et al., 2014). Interestingly, the move to smaller-scale modes in an urban environment appears to be costly. However, as shipments are small and dispersed, delivery with large-scale modes (larger than a van) can become counterproductive and smaller modes (mopeds, bicycles) are more flexible. Experiments with the use of waterways are underway in several countries to test for bundling opportunities; evidence of sustained success so far is only available for waste and construction material (Wojewódzka-Król & Rolbiecki, 2019). From a global perspective this has limited impact on emission levels, due to a limited availability of waterways in or near cities. Also, rail freight transport in an urban context has been considered (using trams, mostly) but the logistics costs of this technology have shown to be prohibitively high (Elbert & Rentschler, 2022).

3.3 Asset utilization

Assets used in logistics include containers, vehicles and distribution centers. A high utilization of these assets is important for efficient logistics processes. Vehicles are generally not used to full capacity. Approximately 1 in 5 trips is empty and average load factors of truck seldomly exceed 50% (CE Delft, 2020). Various solutions exist to make goods movements efficient. The vision of the long-term future of logistics known as "Physical Internet" (PI, Montreuil, 2011) centers around this idea of improving the utilization of assets through various advanced innovation, to an extent that decarbonization targets would come into reach. (Kim et al., 2021) find that the application of PI principles for urban distribution could reduce the required number of movements for the same demand to about 60% of their current intensity. In the context of decarbonization objectives, an important effect of improved asset utilization is that the stock of assets themselves will be reduced, alleviating the task of transitioning to more environment friendly load units, means of transport and warehouses. The potential of measures feasible in the short term is considerably lower, however and lie in the range of a 20%–25% reduction of traffic (See e.g. Van Duin et al., 2021 for the urban context and Balcombe et al., 2019 for international shipping).

Companies usually already exploit many possibilities that lie within their own power, as it is in their own interest to maximize efficiency. This includes appropriate choices of packaging, vehicle type, inventory choices, routing and scheduling of trucks. Constraints imposed by clients, like time windows for pick-up or delivery, will limit their degrees of freedom to optimize movements. Collaboration with other companies could allow them to bundle shipments and reduce the number of vehicles per ton of freight moved (Aloui et al., 2021). Bundling of movements can also occur between passenger and freight movements, by using public or private transport passengers to accompany deliveries (Mohri et al., 2023; Cavallaro & Nocera, 2022). Collaboration can also extend to inventories which allows further consolidation of shipments and reduces the warehouse space needed. An illustration of this principle is given in the Physical Internet

Manifesto (Montreuil, 2012). It states that the US has around half a million warehouses, each of which are used only by a limited number of companies. As each company also typically uses only a limited number of distribution centers, the potential for reducing the use of warehouse space in the country is enormous, provided that these companies collaborate. This could be possible through the use of digital platforms allocating warehouse space across companies. Finally, loading units such as totes, boxes, pallets, cages and containers are used to allow easy handling and storage of products. Clearly, these units ideally should fit tightly around the shipment to minimize space requirements. Standardization between loading units is also important to allow optimal usage of transport space. The Physical Internet PI vision focuses on a harmonization of these measures around modular, standardized "Pi-containers". The integrative approach taken in the PI narrative has become the subject of a new movement in the research world of purposive, systemic design, building on existing literature (see Münch et al., 2024 for a review). While of strategic importance for the decarbonization problem as connected to several of the strategies and measures discussed here, it will not be sufficient to achieve decarbonization targets. Fundamentally, the PI narrative is efficiency focused.

3.4 Energy efficiency

Reducing the use of energy per kilometer is an important strategy for decarbonization of freight transport. Although the effects in terms of carbon emission reduction are modest compared to other measures, its introduction is relatively easy due to immediate financial benefits and resulting short payback times (Smokers et al., 2014). Typical measures include (ALICE, 2019):

- Vehicle and vessel technology improvements to reduce rolling resistance or aerodynamic drag, vehicle/vessel weight and improved engine efficiency.
- Behavioral change towards use of technology (e.g. eco-driving) to reduce energy loss through braking or use during acceleration.
- Accelerated renewal of fleets to increase the use of modern vehicles that comply with newer stricter regulations for fuel efficiency.
- Increase of loading capacity by allowing longer, higher and heavier vehicles and vessels. Governments are hesitant to allow very large trucks, as they may increase accident risk on the road and possibly even shift freight away from railways. In rail transport, double stacking of containers

on wagons has been common outside Europe but is difficult to apply in networks with narrow gauges and bridges. Maritime transport has seen the most visible increase in scale in the past decades, in particular with container ships.
- Speed reduction, particularly popular in maritime transport (known as "slow steaming"), dramatically reducing fuel use of engines (Cariou, 2011).
- Improving logistics operational efficiency by optimized routing and scheduling, both before operations (optimized planning) and during operations (dynamic optimization). Scheduling measures may involve moving operations to off-peak times including nighttime.

3.5 Clean energy carriers

The transition to renewable sources of energy is well underway. Important differences exist between low-emission solutions in terms of costs, constraints to logistic operations, and ultimate effect on CO_2 emission reductions (CSRF, 2020; Rogstadius et al., 2024), with battery-electric engines emerging as dominant solution for land transport, with biofuels being an intermediate, short-term and small-scale solution to create cleaner engines and reduce the consumption of fossil fuels (ALICE, 2019; Meyer, 2020; Yu et al., 2024). The electricity infrastructure needed to power cars, trucks and trains is expected to develop together with the overall landscape for electricity use in industry and housing. Already now, battery-electric trucks perform over longer distances at costs comparable to that of diesel vehicles. Various alternatives exist for battery charging, through nighttime depot charging, daytime public charging stations and charging while driving using overhead cables or induction loops (World Road Association, 2023). The volume of battery electric transport is expected to grow together with the expansion of electricity grids worldwide.

Intercontinental, long distance transport modes are challenging to convert to fully electric operations. Biofuels (biodiesel, hydrotreated vegetable oil (HVO) and biomethane) have the potential to largely replace petroleum product consumption in ocean vessels and airplanes (Chiaramonti et al., 2021). Producing these fuels to decarbonize road transport is infeasible, as this would require such an increase in land use that it would compete with food production. Hence, for road transport, it is only a temporary solution. While synthetic fuels like e-ammonia, e-methanol or hydrogen are also contenders, these are not without limitations due to the inefficient and intermittent use of clean energy, methane slip from engines, or safety and health concerns with ammonia, competition with primary use of hydrogen in industry and overall high costs (TNO, 2023). Therefore, for intercontinental transport, biofuels seem a serious alternative for the longer term.

The next section discusses the relationship between these decarbonization strategies and freight transport planning.

4. Role of freight transport planning in decarbonization

Freight transport planning will be challenged by changes in technology and behavior, directed to reduce the carbon emissions of logistics. All these changes will affect the demand for space which is now available for logistics activities, including storage, movement and handling of freight. Below we discuss the main decarbonization strategies and relate it to key areas of transport planning. From this discussion, we summarize the main directions in which transport planners can be active to support freight decarbonization.

4.1 Demand reduction

Following directions for decarbonization through demand reduction, freight transport planning could facilitate emission reduction in a number of ways.

Spatial planning could support changes in land use aimed at congestion-free and emission-free access to cities, shortening last-mile delivery distances. With the growth of fast e-commerce and omni-channel distribution, freight traffic has become an individualized and customized service for citizens (Risberg, 2023). Spatial planning facilitates this acceleration of flows when replacing industrial activities with new residential areas (Haarstad et al., 2024). Remedies could involve city distribution centers, transshipment hubs or buffering places at the edges of cities, close enough to consumers to allow delivery by slow and environment-friendly modes (McLeod & Browne, 2023).

The development of 3D printing as a way to produce products at home will depend on access to raw materials from material hubs, like seaports, bulk processing plants and local distribution points. Allowing such hubs to locate close to population centers, or printing shops to develop around such material hubs requires support from local spatial planning and zoning policies.

Distance reduction is possible through collaboration between suppliers and receivers in a network. As transaction costs decrease with increasing digitalization, platforms will link these suppliers and receivers in more efficient ways, effectively reducing the need for transport (Rezaei et al., 2020). Distance reduction through dematerialization and circular commodity flows will require space for activities that today only have limited visibility: repair and maintenance, recuperation of materials from waste (also known as "urban mining", Xavier et al., 2023), sorting and regeneration of materials, and storage.

4.2 Use of transport modes

Space requirements around large-scale mode operations are different than for road transport, and include the following:

Transport infrastructure—the need for an extension of infrastructure is high, if a significant mode shift is to be realized (Tavasszy & Meijeren, 2011). This requires international planning of large-scale extensions of rail and waterways infrastructure, realization of rail connections and sidings for shippers (manufacturing and distribution), and realization of terminal locations at strategic hub locations.

Demand management is needed for modal shift in the sense of changes in supply chains, decelerating flows and keeping larger inventories with low-frequency transport. In many cases, companies will want to maintain high-frequency shipments for a part of their clients (Groothedde et al., 2005; Dong et al., 2018). The new regime will involve additional space requirements, for storage and transshipment. Also, coordination with intermediate transport nodes may need to be facilitated. Information systems that predict the availability of infrastructure and traffic flows may be needed to dynamically synchronize flows.

In the urban space, shifting to other modes is only possible if short-term parking spaces for two-and three-wheelers are available, as well as room for parcel lockers for public use. Squares in cities, also called mobility hubs or city hubs, can bundle these uses of space with other functions (Chetouani et al., 2023). Use of waterways requires loading and unloading quays with space for storage and access.

Internalization of external costs based on decarbonization targets could result in significant increase in costs of road transport (at least, if operating with combustion engines) and, given the current cost elasticities of road transport, affect the balance between modes.

4.3 Improved asset utilization

The consequences for spatial planning of an improved use of assets are numerous. As different load units and vehicles have different spatial footprints, a change in asset type will affect the use of space. For example, bicycles, vans and trailer trucks have different space requirements when moving, but also when parked or used for loading and unloading. Replacing one van with 10 cargo bikes or 10 vans with one big truck will both reduce carbon emissions, but also negatively affect the space available for other road users. Practice guidelines or research on these metrics, for use by urban planners and engineers, are lacking however (Kin et al., 2024; Buldeo Rai et al., 2022; Cruz-Daraviña & Suescún, 2021; Sanchez-Diaz & Browne, 2018). At a higher level, spatial planning will be affected by location choices and use of warehouses. If collaboration would be possible to improve the use of distribution centers, some of these would be abandoned, and some would grow to a multiple of their current size. Clearly, such changes can only occur if they are facilitated by spatial planners to allow the abandoning or extension of warehouses, through changes in claims for logistics real estate and access infrastructure.

4.4 Energy efficiency

Freight transport planning in the sense of private, firm-level logistics management is the primary source of decision making for these improvements. Within the scope of this chapter, however, we are concerned with the planning activities that include the public spheres. It is interesting to look at the effects that optimization of energy efficiency has on the use of space. Here we find several relationships of importance:

- Increasing the scale of means of transport requires more time and space to load, unload and move freight. Very large trucks; longer, double-stack container trains; ultra large container sea carriers: these all require network extensions.
- Speed reduction will have the network effect of reducing the carrying capacity of the services, implying a higher utilization of existing assets and perhaps a need for more vessels and trucks to move the same amount of freight per unit of time (Cariou, 2011).
- Optimization of routing and scheduling may be very effective to reduce transport costs and energy used. It can be facilitated by public information on traffic disruptions (road maintenance, bridge openings) and accurate transport times. Uncoordinated optimization may result in traffic congestion on high access corridors, or unwanted movements in sensitive areas (e.g. routing

through residential areas, possibly even during night time). Access limitations or incentives to coordinate routing may be needed to protect these areas.
- By far the most important measure to reduce energy consumption in freight transport has been the regulation of engine emissions. Internationally, diesel engines may still see some efficiency gains, but the biggest next step is expected from full electrification. At local level, zero emission zones are being introduced, which are more aimed at protecting citizens than at achieving a global emission reduction (McKinnon, 2023). Around the city edges, emissions have shown to increase, due to additional traffic with non-zero emission engines. Although this does not offset entirely the local emission reduction, the rebound effect is significant (De Bok et al., 2022).

Planning activities can help to provide necessary infrastructure, signal difficulties with the use of public space and to protect sensitive areas, by means of zoning and regulatory measures. This may reduce the degrees of freedom to optimize logistics activities, but also stimulate firms to invest in decarbonization.

4.5 Clean energy carriers

Clearly, freight transport planning has an important role to play, to help achieve a transition to clean energy carriers. On the private side, many, if not all transport management decisions are affected. From routing and scheduling to fleet management, service models and strategic network development, many logistics decisions will need reviewing once electric transport becomes mainstream. Given the scope of this chapter, we will not delve into this further.

The use of public space will see many changes as a result of electrification, and planning activities will need to take into account the emerging requirements for charging facilities. Much will depend on the course of the energy transition in the coming decades. Development of new sites for production and storage of renewable fuels may result in the creation of new freight traffic generators. Biofuels have high volumes and low densities, which favors large-scale modes of transport. E-fuels and hydrogen related production would involve high volumes of liquids, which may require entirely new pipeline networks, as technological requirements are high. Additional land take compared to direct electrification is high as production requires three times as much renewable energy (CSRF, 2020; Ainalis et al., 2023). Distribution of these fuels to fueling stations will involve high volumes of trucks compared to current fuels, especially in the case of hydrogen and require extensive safety measures, especially in the

Table 3 Summary of interactions between freight transport planning and decarbonization.

	Land use and infrastructure	**Demand management**	**Information and communication technology**	**Regulatory and fiscal**
Demand reduction	Hub location, new circular supply chains	Shipper/receiver collaboration (trade)	Trade and inventory platforms	Internalization for demand reduction
Mode shift	Intermodal terminals and line infrastructure	Coordination with terminals, space for decelerated supply chains	Information systems supporting synchromodal transport	Internalization of external costs
Asset utilization	Warehouse relocation and redevelopment	Horizontal collaboration between shippers (shipments)	Transport capacity platforms	Support for fleets and real estate portfolio renewal
Energy efficiency	Infrastructure for large-scale means of transport Zero emission zones	Horizontal collaboration between carriers (trips)	Traffic and transport time information, coordination of routing and scheduling	Protect sensitive areas for routing impacts Regulation of engine emissions
Clean energy	Major traffic generating sites, New infrastructures Support for charging facilities	Collaboration to manage demand for electricity	Charging station availability information	Internalization of external costs depending on embedded carbon

case of ammonia (TNO, 2023). The space requirements for bio-based, liquid or gaseous energy carriers may therefore be prohibitively high.

The electrification of transport will have its own new demands on space. Typically, charging times are longer for electric trucks than for diesel trucks, which may create pressure on charging points, requiring new buffering zones or a re-arrangement of the spatial design of charging areas. At the same time, firms equipped with own depot charging facilities who can complete operations on one battery charge, will not require use of public charging. These are typically local retail or last-mile delivery operations, which have short-distance daily missions. Dynamic charging will also alleviate pressure on charging stations, as it uses the existing transport infrastructure for charging. A special category of charging facilities which is relevant for freight planning, is opportunity charging (Teoh, 2022) which used time during loading/unloading stops.

5. Summary

The table below summarizes the relationship between decarbonization strategies and different areas of influence of freight transport planning. It appears that dominant areas include (1) targeted land use and infrastructure design, (2) multi-company demand management, (3) support to public, open access information and communication technology and (4) development of new regulatory and fiscal policies (Table 3).

While these areas may not be immediately associated with transport planning instruments, which are traditionally found in the sphere of spatial design and governance of the use of space, they also cannot be viewed in isolation to these instruments. Together they highlight in which directions freight transport planning should be effective in itself, supportive of other polices, guiding other policies, or extended in its skills and powers, in order to lead to successful decarbonization of freight transport.

6. Conclusions

The discussion above shows that there are many ways in which freight transport planning can influence decarbonization. An important angle is the 5 strategies that planning can support: demand reduction, modal shift, improved asset utilization, increased energy efficiency and clean energy carriers. Some strategies are believed to have limited decarbonization potential but can be effective on the short term ("low hanging fruit", especially energy efficiency) while others can be seen as the reverse (especially, clean energy). All are important because of this dichotomy: as long as small improvements can be implemented on the short term; they have a longer time to work through until the years that decarbonization targets have to be met. There are important relations between these strategies. An important synergetic relation is between asset utilization and clean energy: the better we utilize our assets, the fewer assets we have to change if a technology switch has to be made. Another salient relationship of opposing effects is between clean energy and modal shift. The main argument that drives the idea to shift flows away from road transport, is its high level of CO_2 emissions per unit of freight moved. Once the switch has been made to renewable energy, this argument will lose in strength and importance. The structuring of these measures into a grand strategy for the decarbonization of freight transport is a clear need from practice, and still requires significant research.

New work is needed that combines these directions and creates robust roadmaps, or pathways of change, with sufficient plausibility that decarbonization targets can be achieved. This research will need to take into account not just the deep uncertainty surrounding the major factor of the energy transition, but also address the dynamics of systemic change. As the targets are time bound, some knowledge of the dynamics of decarbonization is needed. The underlying need for knowledge involves the autonomous behavior of the system: what are typical timelines for decision making, for implementation of decisions, and for propagation of effects, towards a final decarbonization impact? Surprisingly, the literature offers very little insight in these critical areas.

Freight transport planning can contribute to the implementation of all five strategies. It should contribute to the combined and aligned use of infrastructural, informational, managerial and fiscal instruments. The discussion in this section has shed a first light on this alignment. The paper explains how all instruments can be useful and support each of the five strategies in different ways. The literature on these measures remains fragmented and research is lacking on a targeted alignment of measures, to maximize the chances for success with decarbonization. Our focus has been on the public function of freight transport planning. Within the public spheres, the application of these instruments in the context of the five strategies will require involvement of different public stakeholders. In addition, alignment is needed with private stakeholders who do their own freight transport planning, optimizing for the benefit of their own company or supply chain. The combined development, or co-design of an effective theory of change (Dhillon & Vaca, 2018; Churchman et al., 2023) is a very urgent task to be taken up together by researchers and practitioners.

Appendix A

Table A1 Decarbonization measures for freight transport explained.

	Solutions	Description	More info
Demand	Supply chain restructuring	Redesign of a logistics network's nodal points, distribution hierarchy and inter-related transport flows to minimize distances traveled and optimize load factors.	WEF (2009); (ALICE, 2020)
	Localization and nearshoring	Localizing production close to consumption, such as agriculture produce, and nearshoring of inbound materials closer to manufacturing.	WEF (2009)
	Decentralization of production and stockholding	Moving production stockholding and sales closer to consumers. As example, we can see many retailers that are expanding their inventory management to include stores.	McKinnon (2018)
	3-D Printing	3-D printing of spare parts, products or parts of products that can be combined with manufacturing closer to markets and thus reduce freight transport demand, while acknowledging that raw materials still need to be transported.	(ALICE, 2020)
	Dematerialization	Reducing the physical quantify of goods/products/ packaging needed to delivery consumer value. Possibilities are product re-design, waste minimization, recycling, digitization, miniaturization, material substitution, and postponement of dispersing products to new markets.	McKinnon (2018); (ALICE, 2020)
	Consumer behavior	Influencing consumer behavior through awareness-raising and education on their purchasing behavior and encouraging	WEF (2009)

		recycling. Last-mile home delivery can reduce carbon emissions if it replaces a consumer shopping journey with a motorized vehicle. It needs to consider lead time and delivery time and counter the negative impact of fragmented flows due to on-demand logistics, instant delivery and omnichannel distribution.	
Transport modes	Modal shift	Structurally switching freight to lower-emissions modes. This can include switching air freight to electrified aircrafts and unmanned aerial systems (highest impact but small scale), switching long haul road transportation to rail or waterways (highest potential), and switching from trucks and vans to motorbikes and bikes in cities (most urban side-benefits).	WEF (2009); McKinnon (2018)
	Multi-modal optimization	Optimizing the combination of different modes and linkages between them by adding and optimizing transshipment possibilities. An example is optimizing ship-port interfaces to reduce the waiting time for ships. It includes minimizing waiting times for trucks (or other modes) at terminals.	ITF (2018); WEF (2009); (ALICE, 2020)
	Synchromodality	Optimizing and flexible use of different modes and routes in a network under the direction of a logistics service provider, so that the customer (shipper or forwarder) is offered an integrated solution for its (inland) transport	McKinnon (2018); (ALICE, 2020)

(continued)

Table A1 Decarbonization measures for freight transport explained. (*cont'd*)

	Solutions	Description	More info
Asset utilization	Load optimization	• Adjust truck size to load. Higher freight efficiency is achieved as the amount of freight hauled per litre of fuel used, so the fuller the trailer the better overall efficiency. Matching the size of the truck or van with the load volume contributes to efficiency. • Optimizing use of truck space. Optimize the loading of vehicles taking the vehicle and freight dimensions into account, which can be enhanced using software. • Mixed load/weight volume. Non-traditional heterogeneous pallet built of a mixture of products where the degree of pallet density is lower compared to their traditional counterparts. Improvements of vehicle fill through physical techniques such as efficient unit loads, and a combination of mechanical and manual loading may be necessary.	IEA (2017); (ALICE, 2020)
	Load consolidation	Bundling shipments across product categories with similar shipment characteristics (destination, time constraints). This can be realized through • Horizontal collaboration (companies at the same level of the logistics chain, either shippers or providers, form partnerships to bundle loads or make use of the same vehicles/assets)	IEA (2017); WEF (2009); (ALICE, 2020)

	• Combined freight and warehouse exchange platforms (platforms for exchanging information between carriers, freight forwarders/LSPs and shippers to facilitate new orders and collaboration, including backhauling) • Pooling and bundling/cross-docking that are optimized to facilitate load consolidation from different suppliers/shippers • City consolidation centers (group shipments from multiple shippers and consolidate these onto a single truck for delivery with a city or urban area) • Crowd-shipping (recruiting citizens to serve as couriers using their private vehicles to pick up and drop off parcels along routes they are taking anyway) Many software management tools are available to help reduce empty running by finding additional freight to haul given each fleet's capabilities with routes, equipment, time, and other variables.	
Modular packaging and boxes	Redesign of product packaging and transport boxes/containers for optimal fit to product and for modularity, to allow efficient handling and consolidation. This can be combined with re-usable plastic cassettes (RPCs) and re-usable intermediate containers (RICs).	
Back-hauling	Refers to the practice of picking up and/or delivering cargo on return or round trips as compared to returning with empty vehicles or vessels.	IEA (2017)

(continued)

Table A1 Decarbonization measures for freight transport explained. (*cont'd*)

	Solutions	Description	More info
	Logistics centers and warehouse management	• Increase storage density. Examples are improve pallet stacking, automated systems and use of small(er) shuttles • Energy efficiency measures. Examples are LED lights, smart-sensors, high frequency battery chargers and Lithium batteries, and thermal insulation • Open warehouses and transport networks to make us of idle capacity	WEF (2009)
Fleet efficiency	Cleaner and efficient technologies	• Tires. Low rolling resistance tires can be designed with various specifications, including dual tires or wide-base single tires • Aluminum wheels. These wheels replace common steel wheels and are intended to reduce vehicle weight, heat dissipation, and improving fuel efficiency. • Idling reduction technologies. These include auxiliary power units and generator sets, battery air conditioning systems, plug-in parking spots at truck stops and thermal storage systems. • Automatic transmission. Moving from manual to automatic/automated manual transmission can greatly improve efficiency. Adding gears, reducing transmission friction and using shift optimization in manual automated or fully automated transmissions can also improve drivetrain efficiency	IEA (2017); IRU (2017); ITF (2018)

	• Low viscosity lubricants. Oils with less internal resistance to flow that decrease engine mechanical losses, thereby reducing fuel use. • Oil by-pass filtration system. Secondary filtration unit with the purpose of super-cleaning engine oil, extending lifetime. It has high contaminant-holding capacity and filters out the smallest particles to include sludge and soot in special cases • Battery electric vehicles. The efficiency of electric motors is much higher that internal combustion engines.	
Efficient vehicles and vessels	• Fleet renewal. Effectiveness and cost-effectiveness of early replacement of old vehicles to improve air quality, reduce dependence on oil, CO2 emissions and increase road safety. • Light-weighting. Broadly, all HDV vehicle types except utility trucks could cost-effectively reduce weight by upwards of 7% within the next ten years. Weight advantage offers a greater degree of freedom in vehicle design and performance. • High-capacity vehicles. Refers to an increase in a truck´s size with heavier payloads, leading to a smaller proportionate increase in fuel consumption. Hence, leading to less fuel than smaller trucks per each unit of freight. Duo-trailers are a specific type. • Autonomous trucks. Driverless vehicles operated remotely could increase fuel economy. • Autonomous rail services. Driverless trains which are fully automated and are operated remotely.	IEA (2017); IRU (2017); ITF (2018)

(continued)

Table A1 Decarbonization measures for freight transport explained. (*cont'd*)

Solutions	Description	More info
Optimizing diesel systems	New cleaner diesel system that includes an efficient engine and optimized combustion system with the most advanced fuel-injection, turbocharging and engine management strategies coupled with advanced emissions controls and after-treatment technologies including particulate filters and selective catalytic reduction (SCR) systems, all running on ultra-low sulfur diesel fuel.	IEA (2017); IRU (2017)
Driving behavior/ eco-driving	Practice of driving in such a way as to minimize fuel consumption (i.e. coasting before engine breaking, limit harsh breaking/acceleration+), the emission of carbon dioxide and vehicles wear and tear.	IEA (2017); IRU (2017)
Fleet operation	Platooning. Refers to the practice of driving heavy-duty trucks (primarily tractor-trailers or rigid trucks) in a single line with small gaps between them to reduce drag and thereby save fuel during highway operations.Routing. Optimizing delivery routes through the deployment of GPS and GIS to assist drivers in finding shortest route or avoiding traffic congestion.Retiming. Refers to shift to off-hour (or night-time) logistics operations and deliveries.Slow steaming. The practice of operating transoceanic cargo ships, especially container ships, at significantly less than their maximum speed.De-speeding.	IEA (2017); IRU (2017); McKinnon (2018); WEF (2009); ITF (2018)

		The practice of operating trucks, especially long-distance trucks, at significantly less than their maximum speedPlanning of use. Reducing the non-productive operations of trucks, trains and ships (e.g. train coupling, truck maintenance, ship cleaning) through better planning Maintenance. Moving from preventative to predictive maintenance that optimizes the use of vehicles/vessels and improves planning of their use.	
	Telematics/TMS	Telematics is technology that combines telecommunications and global positioning system (GPS) information (i.e. time and location) to monitor driver and vehicle performance from the central authority or dispatching unit. Truck fleets can improve operational efficiency, boost driver safety, and reduce high-cost vehicle repairs by implementing these communication systems. Telematics is often combined with boarder Transport Management Systems (TMS).	IEA (2017); IRU (2017)
	CNG/LNG	Medium heavy-duty compression ignition engines can be designed to run solely on methane using positive ignition systems, in form of compressed natural gas (CNG) –typically for larger vehicles- or liquefied natural gas (LNG), for smaller trucks.	IEA (2017); IRU (2017)
	Biofuels	A range of biofuel options (biodiesel, hydrotreated vegetable oil (HVO) and biomethane) has the potential to partially replace petroleum product consumption in heavy-duty road transport, ocean vessels and barges, and airplanes.	IEA (2017); IRU (2017); ITF (2018); IATA (n.d.)

(continued)

Table A1 Decarbonization measures for freight transport explained. (*cont'd*)

	Solutions	Description	More info
	Hydrogen	Trucks using fuel cells and hydrogen are essentially electric vehicles using hydrogen stored in a pressurized tank and equipped with a fuel cell for on-board power generation	IEA (2017); IRU (2017); ECF (2018)
	Electric/hybrids	Parallel hybridization may be the most cost-effective near-term technology option for municipal utility vehicles, while electric hybridization tends to be the best hybridization option for most other mission profiles. Electric roads systems (ERS) consist of infrastructure (e.g. catenary (overhead lines) or inductive energy transfer from the road) which supplies electrical energy to trucks while they move. Trucks maintain their operational flexibility as they can operate outside the ERS with a hybrid drive train or by having a sufficient battery.	IEA (2017); IRU (2017); ECF (2018); CSRF (2020)

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