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Behavioral Efficiency Improvement via Freight Digitalization as a Viable Near-Term Strategy to Decarbonize the Difficult-To-Abate Road Freight Sector in China and Other Developing Countries

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The containment of road freight transport emission growth is a significant challenge to climate change mitigation, as the road freight sector has been one of the fastest growing sources of greenhouse gas (GHG) emissions and is considered particularly difficult to decarbonize (ITF 2021). Globally, this sector accounts for approximately one-fifth of the world's oil demand and more than one-third of transport-related CO_2 emissions (IEA 2017). The International Transport Forum (ITF) estimates that world freight transport demand (across all modes) will grow more than twofold in the next thirty years (ITF 2021), presenting a significant challenge to the UN's climate change mitigation agenda. This challenge is exacerbated as low- and middle-income developing countries, often relying on road freight as a key pillar of domestic economic growth, are expected to account for most future surface freight activity growth (ITF 2021; SLOCAT 2021a); however, these countries are ill prepared to confront the mounting climate change mitigation pressure (Timperley 2021; UN Environment Program 2022; Wolf 2022).

Despite its clear carbon and energy significance, road freight transport receives much less attention from policymakers and researchers than does road passenger mobility, and the current policy framework is deemed insufficient for meeting the goals set by the Paris Agreement (SLOCAT 2021b). Among existing UNFCCC commitments through July of 2022 for transport emission mitigation, a substantial amount of focus is being placed on low-carbon technology solutions such as electrification, alternative fuels and vehicle efficiency improvement (GIZ and SLOCAT 2022; Gota, Huizenga, and Kaar 2016). While these efforts are mostly led by high-income economies, the implementation of these strategies in the context of developing countries aiming to decarbonize their transport systems may encounter several critical challenges in the short term.

First, as developing countries have lower levels of income and vehicle ownership than do other countries, road freight often plays a larger role in their transport systems (IEA 2021; Mulholland et al. 2018) and, hence, may present a greater mitigation challenge than may passenger mobility. However, the availability of affordable low-carbon transport options, such as electric and fuel-cell heavy-duty trucks, is still very limited, and their deployment progress remains slow (Hao et al. 2019; IPCC 2022). Second, due to the lower level of logistical market development, the absence of the necessary regulatory environment and several other reasons, heavy-duty vehicles in many developing countries are less energy efficient than are their counterparts in other countries (Gorham 2022; Greene and Facanha 2019; ICCT 2017b, 2021; McKinnon 2018). However, vehicle usage in these countries may further disincentivize vehicle efficiency improvement and often renders international experience with fuel economy gains irrelevant due to the distinct market conditions in these countries (e.g., excessive fragmentation and intense carrier competition) (ICCT 2017a, 2017b, 2019; IISD 2013; NITTI Aayog, RMI, and RMI India 2021; RMI 2016). Third, vehicle- and fuel-technology-driven decarbonization also requires substantial investments in infrastructure and the scaling up of technology. The total expenditure between now and 2060 along such a pathway, e.g., for China's transport sector, is estimated to be almost $10 trillion, with a large part needing to be invested upfront (World Bank 2022). Without a massive amount of capital and a high degree of technology transfer from high-income countries, such an approach would not be viable in the short term.

Hence, given the significant financial, technology, infrastructure, regulatory and market barriers (Ratledge 2022; Williams 2022; World Bank 2022), developing countries need to explore transport mitigation pathways that are more balanced and can accommodate their own social development and emission mitigation needs (Abdul-Manan et al. 2022; Hodgson 2022; Vandycke and Sehmi 2022). A wide range of additional policies and an all-hands-on-deck approach are needed to decarbonize the road freight sector in developing countries, as there is simply no one-size-fits-all pathway on which to tackle climate change (IPCC 2022; Yang et al. 2022).

The revitalization of the avoid-shift-improve (A-S-I) framework in recent climate change research has called for an increasingly demand-side mitigation approach (Creutzig et al. 2018; Creutzig et al. 2022; IPCC 2022; Zhang and Hanaoka 2022). Avoid and shift measures, in particular, have been recommended due to their cost-effectiveness and great potential in terms of emission reduction (Grubler et al. 2018; Gota et al. 2019; SLOCAT 2021a, 2021b). Within the avoid strategy for transport, one particular dimension that is often overlooked but may offer a potential cost-effective near-term solution to the decarbonization of road freight transport in developing countries is the behavioral aspect of transport end-use services delivery (i.e., business/market behaviors such as the operation of fleets and trucks). Since service delivery efficiency is the product of technology (or drivetrain) efficiency and behavioral (or operational) efficiency (Grubler et al. 2018; IPCC 2022), improving operational efficiency by increasing the vehicle load factor, boosting daily activity levels and reducing empty running in the context of road freight can all improve the degree of asset utilization and reduce excessive travel demand, thus contributing to emission mitigation. Conversely, a reduction in the degree of operational efficiency may offset any efficiency savings from other measures, such as advances in technology, and result in greater total emissions (Gucwa and Shafer 2013).

While freight transport activities in low- and middle-income economies have grown significantly in the past few decades, driven by strong economic development and population growth (IPCC 2022; Mulholland et al. 2018), the freight logistics industry in these countries remains one of the less automated and scaled economic sectors, and a large operational-performance gap remains between developing and developed countries in terms of this sector (IISD 2013; Londono-Kent 2009; McKinnon 2018; World Bank 2018). For trucks, which remain the dominant mode of surface freight transport in many emerging economies, their logistics markets are typically characterized by high degrees of fragmentation, low degrees of vehicle utilization and an excessive number of empty-running journeys, resulting in considerable fuel consumption and economic costs (CATARC 2017; Davies, Nair, and Qu 2013a; ICCT 2017a, 2021; IISD 2013; Londono-Kent 2009; NITTI Aayog, RMI, and RMI India 2021; RMI 2016). Although it is unclear to what extent low operational efficiency has led to fast transport energy consumption and carbon emission growth in developing countries, some research suggests that operational factors may be a major contributor to cross-country variations in the levels of transport energy and carbon intensity (Gucwa and Shafer 2013; Schafer and Yeh 2020). Therefore, many studies have recommended the improvement of logistical operational efficiencies as one of the most important means through which to decarbonize the freight transport sector (Greening et al. 2015; IEA 2017; IPCC 2022; ITF 2021; McKinnon 2018, 2022; Mulholland et al. 2018; World Bank 2022).

The wide availability of smart mobile devices and a new wave of digitalization in the road freight sector in recent years have made the improvement of operational efficiency a potentially low-hanging fruit for developing countries. The emergence of the “Uber”-like software as a service (SaaS) business model in many emerging and established markets offers the potential to significantly boost vehicle utilization and bring forth systemic efficiency improvement by popularizing computerized transportation management system (TMS) solutions that traditionally could be accessed only by large logistics firms and fleets (BCG 2021; CATARC 2017; ICCT 2021; IEA 2017; McKinsey & Comany 2019, 2020; NITTI Aayog and RMI 2018; NITTI Aayog, RMI, and RMI India 2021). By connecting carriers with shippers via mobile-internet-based freight-matching platforms, freight digitalization is disrupting the inefficient, conventional manual logistics practices in many developing countries and replacing them with much more effective automated processes (Air Cargo News 2019; DHL 2019, 2020; FreightWaves 2019a, 2019b; Jamal 2021; McKinsey & Comany 2019, 2020; NDTA 2021; News24 2021; PYMNTS 2023; Reuters 2021). For emerging economies that are typically characterized by lower levels of freight infrastructure development and market maturity, digital transformation may help achieve economies of scale in the logistics sector by accelerating the consolidation of both market supply and demand. The direct impacts of digital transformation include improved vehicle utilization, a reduced number of vehicle activities, and likely a smaller HDV stock, which eventually translate into less road freight energy consumption and fewer carbon emissions and a reduction in other negative externalities, such as congestion, pollution, noise and accidents.

While digitalization is one of the new megatrends through which to transform business models and change user behavior (IPCC 2022; Tiefenbeck 2017), the existing discussion of its impact on climate change mitigation in the transport sector has focused largely on consumer demand regarding passenger mobility in urban settings (Diao, Kong, and Zhao 2021; Henao and Marshall 2019). Little in-depth analysis has been conducted on the road freight sector, and an understanding of how to steer this sector toward a better narrative is critically needed (IPCC 2022). Therefore, the purpose of the current research is to start narrowing this important gap. This study utilizes the latest real-world truck operation data and a bottom-up transport-energy model to analyze how digitalization may impact vehicle operations, energy consumption and carbon emissions in the road freight sector in the context of developing countries. A range of data from both public and proprietary sources have been collected from China, one of the world's most dynamic freight logistics markets, which is being rapidly transformed by freight digitalization (CATARC 2017; McKinsey & Company 2019, 2020). The results of the analysis show that by rapidly improving vehicle utilization as a result of digitalization, the potential mitigation effects of operational efficiency gains outweigh those of zero-emission technology adoption in the near term, bending the carbon emission curve of road freight transport much earlier than that prior to digitalization. This is particularly important for developing countries and other countries alike, considering that the window of opportunity for countries worldwide to meet the goals of the Paris Agreement is now rapidly narrowing (Mooney and Hodgson 2023). With the trend of road freight digitalization appearing in many developing countries and given its potentially quick market uptake, the digitalization of trucking may offer a cost-effective near-term solution for the decarbonization of the difficult-to-abate road freight transport sector.

To fully utilize the digitalization strategy to achieve emission reduction, developing countries need to actively promote the digital transformation of their conventional road logistics sector. Policymakers also need to be aware of possible limitations in the application of freight digitalization and take measures against any potential negative effects, including rebound effects, substitution effects and induced demand effects, as a result of the improved degree of competitiveness of road freight against other transport modes.

A comprehensive policy framework including price policies and nonprice regulations and an integrated multimodal freight transport system need to be established to complement the efficiency improvement of freight trucking.

Operational Efficiency as a Key Determinant of Energy Efficiency

Total freight transport CO_2 emissions can be decomposed into four multiplying components using the Kaya identity approach: economic output (*GDP*), freight transport intensity (*TKM/GDP*), transport energy intensity (*E/TKM*), and energy carbon intensity (CO_2/E) (McKinnon 2018). Among these variables, freight transport intensity, i.e., the derived level of freight demand of the economy, is driven more by long-term trends such as economic and industrial structures, the geographic distribution of supply and demand, and the organization of international trade and supply chains and, hence, is unlikely to undergo dramatic changes in the short term (McKinnon 2018; Xu, Chase, and Peng 2021). Likewise, carbon intensity for a given fuel type is relatively fixed. Therefore, most attention has been paid to reducing the degree of transport energy intensity as the key means of freight decarbonization.

For a single laden trip, vehicle energy intensity (energy use per revenue tonne-kilometer) can be shown as follows:

$$\frac{e}{tkm} = \frac{\frac{e}{vkm}}{\frac{tkm}{akm} * \frac{akm}{vkm}} \quad (1),$$

where *e* is the energy consumed, *tkm* refers to the freight tonnage transported over the revenue distance, *vkm* is the number of revenue vehicle kilometers traveled, and *akm* is the available tkm on the selected vehicle. Previous research has shown that in equation (1), the denominator always increases faster than does the numerator due to the square-cube law; that is, the degree of energy intensity declines with larger vehicle carrying capacity (*akm*/*vkm*) and greater capacity utilization (*tkm*/*akm*) or with a greater load factor (*tkm*/*vkm*) (Gucwa and Shafer 2013; Schafer and Yeh 2020). This conclusion suggests that energy intensity is higher during empty-running trips, compared to other types of trips, because the truck is not carrying any cargo.

Equation (1) can then be generalized to calculate the aggregate energy intensity for the entire vehicle stock, as shown in the above Kaya identity decomposition, and arrive at the following rearranged specification:

$$\frac{E}{TKM} = \frac{\frac{E}{VKM}}{\frac{TKM}{AKM} * \frac{AKM}{VKM}} = \frac{E}{S * vkt * \frac{TKM}{AKM} * \frac{AKM}{VKM}} \quad (2),$$

where capital letter variables represent the aggregate values of the parameters used in equation (1), and total number of revenue vehicle kilometers traveled (*VKM*) is further decomposed into total vehicle stock (*S*) and the average number of annual revenue kilometers traveled per vehicle (*vkt*).

Equation (2) shows that aggregate energy intensity is determined by both technological and behavioral/operational factors (Grubler et al. 2018; IPCC 2022). Technological factors (e.g., drivetrain, fuel economy, and aerodynamics), which are driven primarily by R&D, contribute directly to reducing energy input *E* in the numerator. In contrast, behavioral/operational factors are influenced to a larger extent by user preferences and choices as a result of sociocultural norms and infrastructure (Dietz et al. 2009; IPCC 2022) and are key determinants of all the remaining variables in the denominator that could contribute to reducing the level of total vehicle activity. While much effort has been devoted to studying the impact of technology improvement on the degree of energy intensity, the behavioral/operational component is poorly understood, and its modeling in most existing transport energy and integrated assessment models (IAMs) remains simplified. This is especially true for freight transport, and thus, operational improvement is critically needed, as transport service demand growth has outpaced fuel efficiency improvement in recent decades (ITF 2019; Milovanoff, Posen, and MacLean 2020).

In the context of road freight transport, behavioral/operational factors refer mainly to the organizational and operational practices of key logistics market players—businesses, fleets, owner-operators, etc.—that have direct impacts on the corresponding variables embedded in equation (2): choice of vehicles in terms of carrying capacity (*AKM*/*VKM*); vehicle mileage utilization, including both average daily/annual revenue vehicle mileages (*vkt*) and the percentage of empty miles; vehicle capacity utilization (*TKM*/*AKM*), i.e., how the full vehicle is loaded; and finally the total amount of vehicles (*S*) that is needed to meet a given freight demand.

Similar to equation (1), greater carrying capacity and capacity utilization (and, therefore, a greater load factor) lead to a lesser degree of energy intensity at the aggregate level, as aggregate intensity is the weighted average of individual values for all vehicles over all trips. Likewise, less empty running contributes to a lesser degree of energy intensity by reducing energy use for nonrevenue travels that have a higher degree of energy intensity compared to laden trips. From the fleet operator's perspective, greater mileage and capacity utilization would result in higher profitability, allowing for investment in more energy-efficient vehicles. A higher number of lifetime vehicle kilometers would further improve the business case of vehicle retrofitting, such as aerodynamics, rolling resistance, and thermal efficiency (ICCT 2019; RMI 2016). Finally, for a given aggregate freight demand (*TKM*), a higher load factor and greater annual vehicle mileage (*vkt*) would lead to a smaller vehicle stock (*S*) and fewer freight trips, producing additional benefits that arise from less congestion, higher driving speeds and less unnecessary travel (Greening et al. 2015).

Operational Efficiency Gap between Developing and Developed Countries

Despite the significant growth in the number of freight transport activities in the last few decades, a large gap in operational efficiency between developing and developed countries remains (World Bank 2018). The trucking industry, as a service sector, remains one of the less automated and scaled economic sectors in many emerging economies, which is reflected in the key operational efficiency metrics discussed in the previous section (Table 1). Compared to established markets in Europe and North America, trucks in emerging markets such as China, India and other developing countries are characterized by a smaller level of average carrying capacity and a lesser degree of vehicle utilization. The lower percentage of large-capacity heavy-duty vehicles in low- and middle-income countries is likely due to the limited availability of high-quality road infrastructure (IEA 2017; NITTI Aayog, RMI, and RMI India 2021), a smaller fleet scale and a large proportion of owner-operators that have limited financial ability to afford higher-cost tractor trailers (CATARC 2017; CFLP 2016; ICCT 2017b, 2021). The lower level of vehicle mileage utilization (as reflected by the high percentage of empty hauls and the low annual vehicle mileages) and capacity utilization, in contrast, can be attributed to excessive market fragmentation, a lower level of market development, and an unsupportive regulatory environment, as well as several other factors (IISD 2013; Londono-Kent 2009; RMI 2016; NITTI Aayog, RMI, and RMI India 2021).

One of the most documented causes of a low degree of logistics efficiency is the fragmentation of freight carriers. As road logistics provide an important source of employment in many low- and middle-income countries, barriers to market

Table 1. Comparison of HDV fleet capacity and utilization levels by major developed and developing economies.

	Empty miles %[a]	Capacity utilization %[b]	annual HFT vkt[c]	Tractor trailer %[d]	LPI 2012-2018 mean rank[e]
China	40%	60%	31,154	20%	27
India	28-43%	50%	37,059	10%	42
Indonesia	25%	45%	61,244	20%	51
Mexico	38%	NA	45,700	52%	53
Brazil	45%	55%	58,215	50%	56
EU	21%	70%	56,208	60%	29
US	20-25%	90%	72,397	70%	10

[a]Data for China, India, Indonesia, Mexico and Brazil, the EU, and the US are from ATRI (2021), EUROSTAT (2022), IADB (2015), Londono-Kent (2009), NITTI Aayog, RMI, and RMI India 2021, and RMI (2016), respectively. [b]Data for China, India, Indonesia, Brazil, the EU, and the US are from McKinsey & Company (2019). [c]Data are 2015 values reported by the IEA (2021). [d]Data for China, India, Indonesia, the US and the EU are from McKinsey & Company (2019). Data for Mexico are calculated using the active highway tractor population from the ICCT (2017b), divided by the total vehicle stock of heavy freight trucks reported in IEA (2021). Data for Brazil are calculated similarly using tractor-trailer registration data from CEIC (2021) and IEA (2021). [e]Data are from World Bank (2018). The LPI ranking of the EU is calculated by comparing the average LPI score of the EU's 27 countries against the overall ranking.

entry are generally low, which results in a high percentage of owner-operators (CFLP 2021; Davies, Nair, and Qu 2013a, 2013b; Londono-Kent 2009). Although this situation is also true for many established markets, the extent to which the market is unconsolidated is much larger in developing economies (IEA 2017). Table 2, for instance, compares carrier structures between for-hire medium and heavy freight trucks in China and interstate carriers in the US. While small carriers—in China's case, owner-operators with only one vehicle—account for the vast majority of the carriers in both countries, the US market is much more consolidated, as large fleets account for nearly half of all vehicles, whereas in China, the share of large fleets is less than 10% of the market total.

Key distinctions in preferences and behaviors between carriers at different scales likely lead to the divergence in their choices of vehicles and operational patterns. Utilizing data from China's logistics market, Table 3 shows that large fleets clearly outperform owner-operators in all operational efficiency metrics. Such a large performance gap may be attributed to marked differences in the level of professional expertise and available resources between owner-operators and large fleets. With low barriers to entry, most market entrants in low- and middle-income countries are financially constrained. As a result, owner-operators typically focus on minimizing upfront costs at the expense of future maintenance and fuel costs and purchase smaller and less fuel-efficient vehicles (ICCT 2017a, 2017b, 2021; NITTI Aayog and RMI 2018; RMI 2016). Moreover, small carriers rely on the more volatile spot freight market that features unfixed routes and drive cycles (Achelpohl 2023; CFLP 2021). Furthermore, owner-operators tend to receive less training regarding efficient driving practices and are less likely to invest in vehicle efficiency improvements than are large fleet operators (RMI 2016). In contrast, large fleet operators have greater financial capability and focus more on the total cost of ownership and asset returns rather than on upfront costs, compared to owner-operators (ICCT 2019; TUC Intelligence 2022a, 2022b). Fleet operators are also more likely to invest in larger-

Table 2. Comparison of carrier structures between China and the US.

	Fleet size by # of vehicles	# of carriers	% of carriers	# of vehicles	% of vehicles
China[a]					
Small	1	5,898,000	94.91%	5,898,000	75.34%
Medium	2-50	313,000	5.04%	1,170,000	14.95%
Large	More than 50	3,507	0.06%	760,000	9.71%
US[b]					
Small	1-19	555,958	95.13%	1,507,572	32.30%
Medium	20-100	24,133	4.13%	955,280	20.47%
Large	More than 100	4,346	0.74%	2,204,195	47.23%

[a]Data for for-hire medium and heavy freight trucks in China are from TUC Intelligence (2022a). The total percentage may exceed 100% due to rounding. [b]Data for interstate carriers in the US are from OODIA (2021).

capacity and more energy-efficient vehicles as well as fuel-saving retrofits and utilize information technologies to optimize freight routes and monitor driving behavior (Bain & Company 2017).

An equally important, although much less reported, contributor to low levels of operational efficiency in developing countries is the high degree of fragmentation among shippers. Increasingly consolidated demand from shippers would lead to more predictable and long-term freight arrangements (Coyote Logistics 2023), allowing carriers to optimize their routes and reduce the number of empty miles, thereby increasing the degrees of operational and energy efficiency. Conversely, a high degree of shipper fragmentation tends to result in more volatile spot demand, which results in one-off transactions, unstable routes, and varying duty cycles, inhibiting operational efficiency improvement. With a lower level of GDP per capita but a faster pace of economic development, many emerging economies tend to have high degrees of shipper fragmentation and many small-sized shippers due to their burgeoning private sectors and the rapid growth of small- and medium-sized enterprises. In China, for instance, the road logistics market remains dominated by spot/noncontractual demand (CFLP 2022b), and the share of the contractual freight market is still very limited (McKinsey & Company 2020). To illustrate, CH Robinson, the largest 3rd-party logistics (3PL) provider in the US, serves 100,000 customers globally (CH Robinson 2023). In comparison, the shipper monthly active users (MAU) of the Full Truck Alliance, China's largest digital freight-matching platform, had 1.3 million customers as of December 2020 (SEC 2021), suggesting a much lower degree of consolidation on the shipper side as opposed to that in the more mature US market.

In the absence of consolidation on either the carrier side or the shipper side, the role of market intermediaries becomes critically important, as it can aggregate both supply and demand (NITTI Aayog, RMI, and RMI India 2021; RMI 2016). While

Table 3. Comparison of key operational attributes between owner-operators and large fleet operators in China.

	Owner-operators	Large fleet operators
Average daily vkt (km)	250[a]	430-550[a]
Average daily number of hours of operation	5.1[a]	8.9-10.2[a]
Capacity utilization	60%[b]	> 60%[c]
Percentage of empty miles	27-36%[d]	10%[d]
Fuel-saving potential due to more efficient driving	N.A.	10%[a]

[a]Data are collected from on-vehicle IoT devices covering over 500,000 trucks and reported by Bain & Company (2017). [b]Data for owner-operators are not available, and thus, a national average value from McKinsey & Company (2019) is reported instead. [c]Data for capacity utilization by large fleet operators are not available, although this factor is one of the major KPIs of for-hire fleets according to TUC Intelligence (2022a) and hence should be higher than the national average value. [d]Data on owner-operators are not available, and so, a national average value based on big data collected from on-vehicle IoT devices (CFLP 2022a) is reported. Data on empty running for large fleets are based on surveys of key road freight transport enterprises conducted by the China Federation of Logistics & Purchasing (CFLP 2022a).

fragmentation among carriers and shippers also exists in many developed markets, such as North America and Europe, logistics intermediaries such as the 3PLs in these markets are well developed and can effectively consolidate and match demand with supply for freight services (IEA 2017; ICCT 2019; NITTI Aayog and RMI 2018). In contrast, in developing countries such as China and India, market intermediaries are much less developed, and multiple layers of freight forwarders and carrier brokers often exist between shippers and carriers, leading to information asymmetry and high transaction costs (NITTI Aayog, RMI, and RMI India 2021; Zhu and Zhu 2022).

Furthermore, the lack of scale in the market could be reflected by the absence of universal transport equipment standards in some developing countries. For example, the lack of a single manufacturing standard for connecting components between tractors and trailers may have resulted in a much lower (1:1) tractor-to-trailer ratio in China compared to the 3:1 ratio found in the US, discouraging efficient logistics practices such as drop-and-hook practices. Moreover, the poor standardization of other equipment, such as containers, also becomes an important barrier to multimodal (e.g., truck-to-rail) transport, where containers should fit on both container chassis and railway cars (ICCT 2019).

Overall, the high degree of fragmentation in many developing countries' logistics markets has resulted in worse operational performance and the deprivation of economies of scale in their corresponding road freight sectors, as exemplified by the China-US comparison of key freight performance metrics in Table 4. Despite being the world's largest vehicle market since 2009, less efficient vehicle mileage and capacity utilization in

Table 4. Key road freight operational performance metrics for China and the US in 2015.

	China	US
Total road freight tkm	5,796[a]	2,899[b]
Share of freight tonnage by road in domestic rail/road/water	78.3%[a]	83.5%[c]
Share of freight tkm by road	48.6%[a]	47.1%[b]
Number (million) & % of heavy/medium freight trucks	5.9 (62%)/3.6 (38%)[d]	2.4 (36%)/4.3 (64%)[d]
Share of tractor-trailers in weight class above 15 tonnes	37%[e]	75%[e]
Trailer to tractor ratio	1:1[f]	3:1[f]
Vehicle capacity utilization	60%[g]	90%[g]
Load factor	16.7/8.6[d]	19.3/6.4[d]
Percentage of empty miles	40%[h]	20-25%[h]
Annual vkt of HFT/MFT	31,154/12,972[d]	72,397/42,267[d]
% tkm by HFT/MFT	89%/11%	74%/26%
Average speed km/h	38[f]	85[f]
Share of logistics costs in GDP	16%[i]	7.8%[j]

[a]Data are from NBS (2022). [b]Data are from BTS (2022). [c]Data are from FHWA (2016). [d]Data are from IEA (2021). [e]Data are from ICCT (2017a). [f]Data are from ICCT (2019). [g]Data are from McKinsey & Comany (2019). [h]Data are from RMI (2016). [i]Data are from CFLP (2019). [j]Data are from TUC Intelligence (2022c).

China likely explain the disproportionately low tkm contribution of medium freight trucks and the need for a much larger heavy freight truck fleet in China—more than 2.4 times compared to that in the US—as well as a higher share of logistics costs in GDP to meet the freight demand, even though China's total road freight tkm is slightly less than twice the size of the US and China's trucking sector carries a smaller percentage of total freight tonnages relative to other modes (rail and domestic shipping).

The lower-level operational performance may then further hinder vehicle efficiency improvement and multimodal transport development, in addition to suppressing overall transport energy efficiency. For example, an oversupply of small carriers has led to low profit margins and widespread overloading in developing countries (Londono-Kent 2009), eventually resulting in unfavorable duty cycles featuring a low degree of vehicle lifetime utilization and reduced driving speed, thus eliminating the business case for efficient technology upgrades (CATARC 2017; IISD 2013; NITTI Aayog, RMI, and RMI India 2021; RMI 2016). The intense competition among truck carriers also impedes carriers from shifting to other lower-emitting freight modes (such as rail), as total road freight charges stay lower for rail than they do for other competing modes (ICCT 2019; NITTI Aayog, RMI, and RMI India 2021).

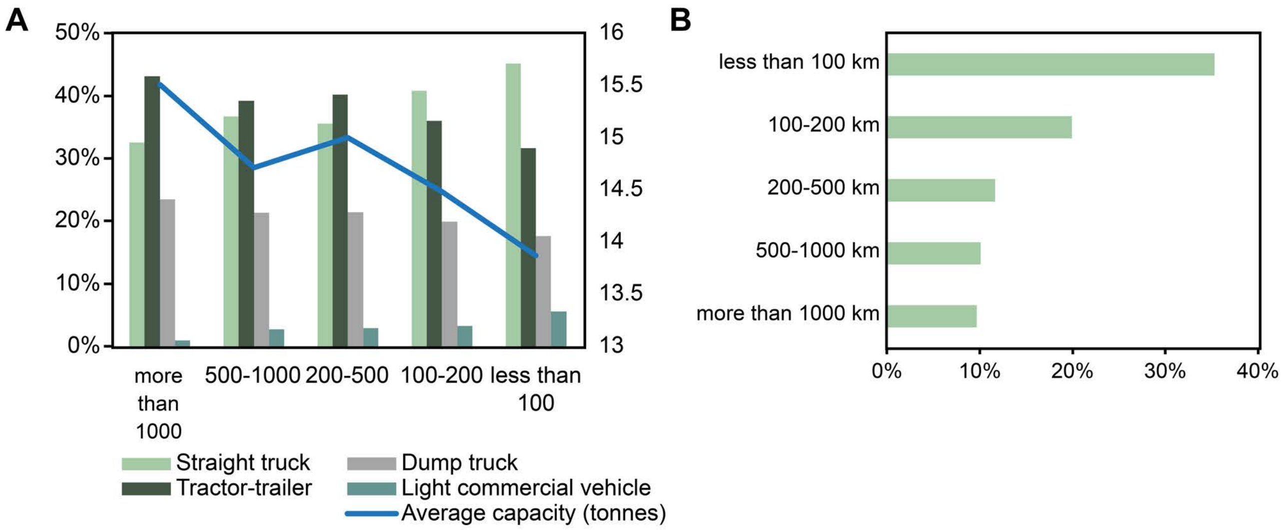
Impact of Digitalization on Road Freight Transport

The widespread adoption of smart mobile devices during the last 10 years and the emergence of an "Uber"-like business model has brought about a critical opportunity to disrupt the conventional practices of road freight transport in developing countries (GeSI 2015) and has the potential to leapfrog to a much more consolidated stage. To investigate the potential energy and climate implications of freight digitalization, this research utilizes proprietary truck operation data collected from China's full truckload (FTL) market, featuring trips matched via online freight platforms and conducted by owner-operators primarily for regional and long-haul deliveries (see the Methods section for a data description).

Figure 1a shows the vehicle type distribution by the total distance of laden trips in the sample. As trip distances increase, the share of straight trucks decreases, whereas the proportion of tractor-trailers and dump trucks increases. Notably, the increase in the percentage of tractor-trailers over distance is not consistent, as its share for the 200-to-500-km range is higher than that for the 500-to-1,000-km range, which is reflected similarly in the higher average carrying capacity (line) for the shorter trip range. This finding confirms the results in Table 4 that China (and many other developing countries) continues to rely on medium freight trucks, especially straight trucks and dump trucks, for a large proportion of its regional and long-haul deliveries (IEA 2017).

Figure 1b shows the average percentage of empty miles by laden distance. Trips under 100 km, mostly urban deliveries, are found to have the highest percentage of empty running, despite being digitally matched. However, as trip distances increase, the share of empty miles by individual trucks quickly declines and eventually converges to approximately 10%, which is very close to the

Figure 1. Vehicle carrying capacity and percentage of empty miles in the sample from 2018. a, Vehicle type distribution and average carrying capacity (right axis) in the sample, categorized by the total distance of laden trips. **b,** Percentage of empty miles in the sample, categorized by the total distance of laden trips. See the Methods section for a data description and the calculation approach to measuring empty running.



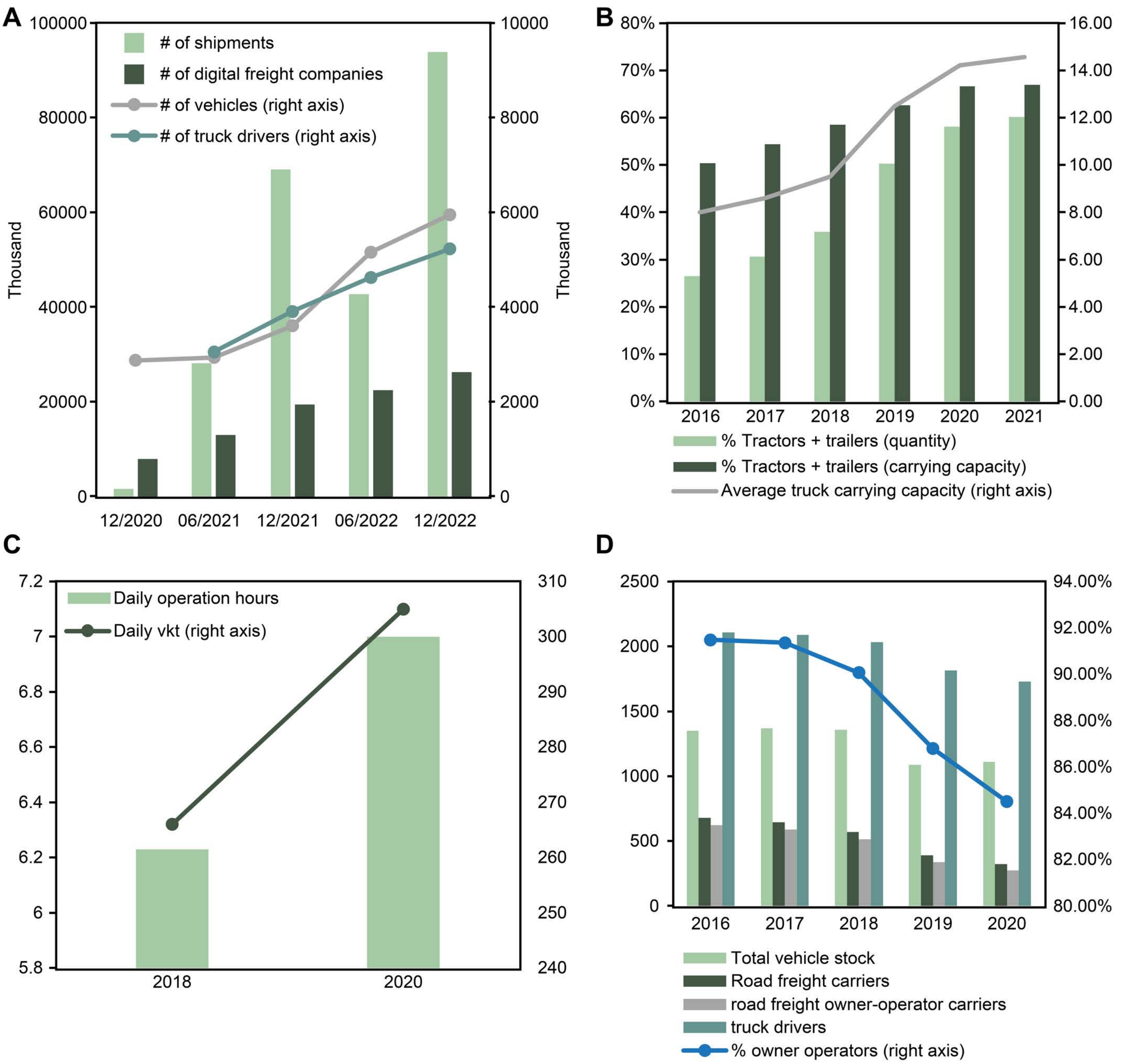
fleet performance percentage reported in Table 3. The reduction in the proportion of empty miles over distance is consistent with the expectation since the opportunity cost for empty hauling is much higher for longer trips and truckers have strong incentives to minimize empty backhauls to improve revenue and avoid loss. In contrast, for shorter journeys such as urban deliveries, the number of backhauling opportunities are very limited (Greening et al. 2015), but the opportunity cost of empty running is also much lower; hence, the share of dead miles is much higher for shorter deliveries.

In terms of average vehicle capacity utilization, the results fall in the range of 87-88% across all duty cycles (intracity, intercity, and interprovince cycles), suggesting a much better cargo-vehicle fit due to improved supply-demand matching in the much-enlarged online pool. However, one caveat is that no cargo volume information is available, and thus, it is not possible to know whether the vehicle is being “cubed out” or “weighed out.” In contrast, the estimated sample daily average revenue vehicle kilometers amounts to 425 km, which again reaches the average performance level of large for-hire fleets (Table 3). Two factors likely explain the 70% increase in the number of daily vehicle activities. By connecting shippers with carriers via mobile applications, online platforms substantially reduce the degree of information asymmetry and eliminate the need to visit small and isolated brick-and-mortar freight markets—the conventional way of load searching for many owner-operators in some developing countries (Kumar 2021; Zhu and Zhu 2022)—especially for medium- and long-haul truckers who are looking for return-trip loads in unfamiliar locations, leading to a significant reduction in the amount of vehicle dwell time. The establishment of a much larger demand pool online further facilitates load searching and enables much faster turnaround. As a result, the average load searching time is estimated to have shortened from 2-3 days previously to approximately 8 hours due to the current more efficient online matching process (CATARC 2017; Chang’an University 2022)

Since the emergence of digital freight matching in China, the market penetration of the new business model has rapidly gained pace. The China Ministry of Transport has released a series of policies and regulations to bolster the development of the digital freight sector (Zhu and Zhu 2022; MOT 2016, 2020). According to surveys conducted by the China Federation of Logistics & Purchasing, the proportion of truck drivers who rely on online freight platforms as their primary freight source has quickly risen from approximately 9% in 2016 to 52% in 2021 (CFLP 2016, 2021). Official statistics on nationwide digitally matched trucking activities started to be compiled in 2020, with the latest report suggesting that in 2022, over 94 million deliveries were conducted by 5.9 million vehicles and 5.2 million truck drivers, equivalent to approximately half of all for-hire vehicles and approximately 30% of all truck drivers in China (Figure 2a) (MOT 2023).

The rapid transition from conventional road logistics practices to the new digital approach, coupled with strong policy drives to improve trucking efficiency and reduce pollution and emission, have likely accelerated the evolution of the logistics market and contributed to operational productivity gains in China’s road freight sector in recent years. Since 2016, the growth of total carrying capacity by for-hire fleets has outpaced that of aggregate road freight tkm, while the number of vehicles has dropped significantly, yielding an 80% average vehicle capacity increase as of 2021 (Figure 2b). The trend toward the use of larger vehicles is mostly attributed to the removal of smaller-capacity vehicles and the rapid growth of the tractor-trailer segment, with the total capacity of the latter expanding from 50% to 67%.

Figure 2. Market penetration of digital freight matching and dynamics of key operational efficiency indicators in China. a, Year-to-date development of China's digital freight industry 2020-2022, reported by the Ministry of Transport (MOT 2023, 2022b, 2022a, 2021). **b,** Average carrying capacity of for-hire vehicles, and among them, the percentages of total quantity and total carrying capacity of tractors and trailers (MOT 2017–2022). **c,** Daily number of vehicle kilometers traveled and operational hours. The 2018 data are from CFLP (2019). The 2020 data are from RIH and SINOIOV (2021). **d,** Total number of trucks (for-hire), road freight carriers (for-hire), road freight owner-operator carriers (for-hire), and truck drivers and the percentage of owner-operator carriers (for-hire). Data are from the Yearbook of China Transportation and Communications (2020).



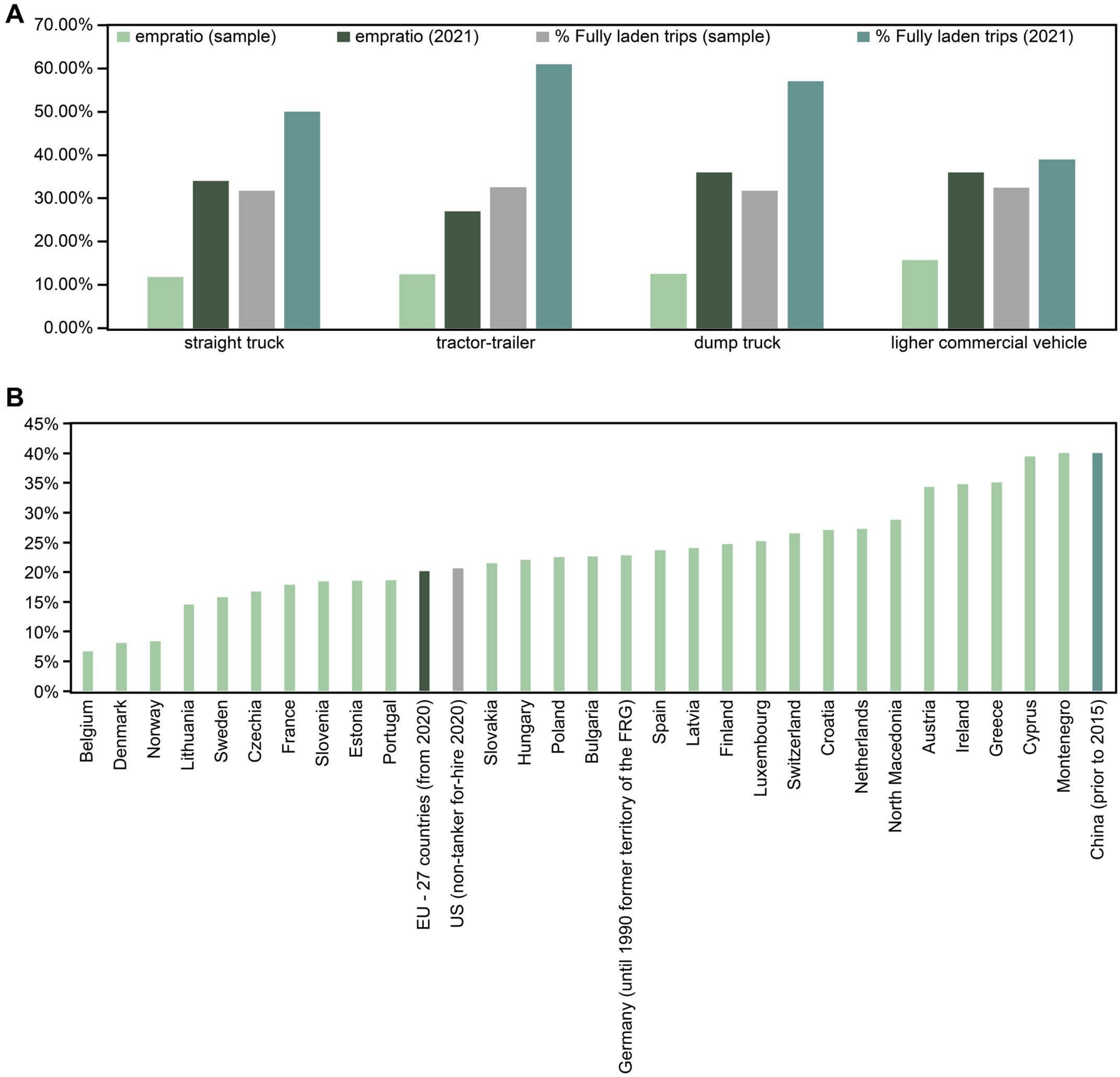
In the meantime, higher daily vehicle mileages and operational hours have been observed (Figure 2c). Apart from the lower amount of dwell time and faster turnaround time, the increased degree of vehicle mileage utilization may also result from increased vehicle speed due to the growing use of toll motorways, which record a much faster average driving speed of approximately 70 km/hour compared to the 45 km/hour recorded on toll-free national and provincial highways (RIH and SINOIOV 2021). The increased usage of toll motorways likely reflects the fact that with much faster turnaround times, truckers are opting for a greater balance between trip time and costs to maximize their revenue (CFLP 2016).

The higher degree of average vehicle carrying capacity and improved utilization due to better load matching, coupled with a strong government push to phase out highly polluting vehicles (CFLP 2021), have likely led to fast market consolidation (Figure 2d). With larger and better utilized vehicles, fewer vehicles and carriers are then required to complete a given level of tkm; thus, redundant and less efficient capacity exits the market. Indeed, between 2016 and 2018, the total number of truck drivers and for-hire road freight carriers both decreased by over a million—predominantly due to market exits by owner-operators—while the total number of for-hire vehicles largely remained the same, indicating an increasing average fleet size. This trend then accelerated after the government further strengthened the requirements for the vehicle carrying capacity of for-hire trucks in 2019 (Yearbook of China Transportation and Communications 2020), with the total number of vehicles, freight carriers and truck drivers each being further reduced by more than two million by the end of 2020.

As the degree of market penetration of digitalization further increases, China's road freight sector is expected to continue evolving rapidly. Figure 3a compares the 2018 sample results on the percentages of empty-running and fully loaded trips with recent national averages sourced from over two million vehicles in 2021 and shows that although shares of fully loaded delivery trips have greatly improved over the three-year course, the latest nationwide share of empty running still lags far behind the 2018 sample values. In an international context, China's current 30% rate of empty miles—though considerably improved compared to the pre-2015 era—remains much higher than that of the US and EU, both of which report an approximately 20% empty miles ratio (Figure 3b). Therefore, substantial room for improvement in terms of operational efficiency remains for China's trucking sector in the near future, as the digitalization trend continues.

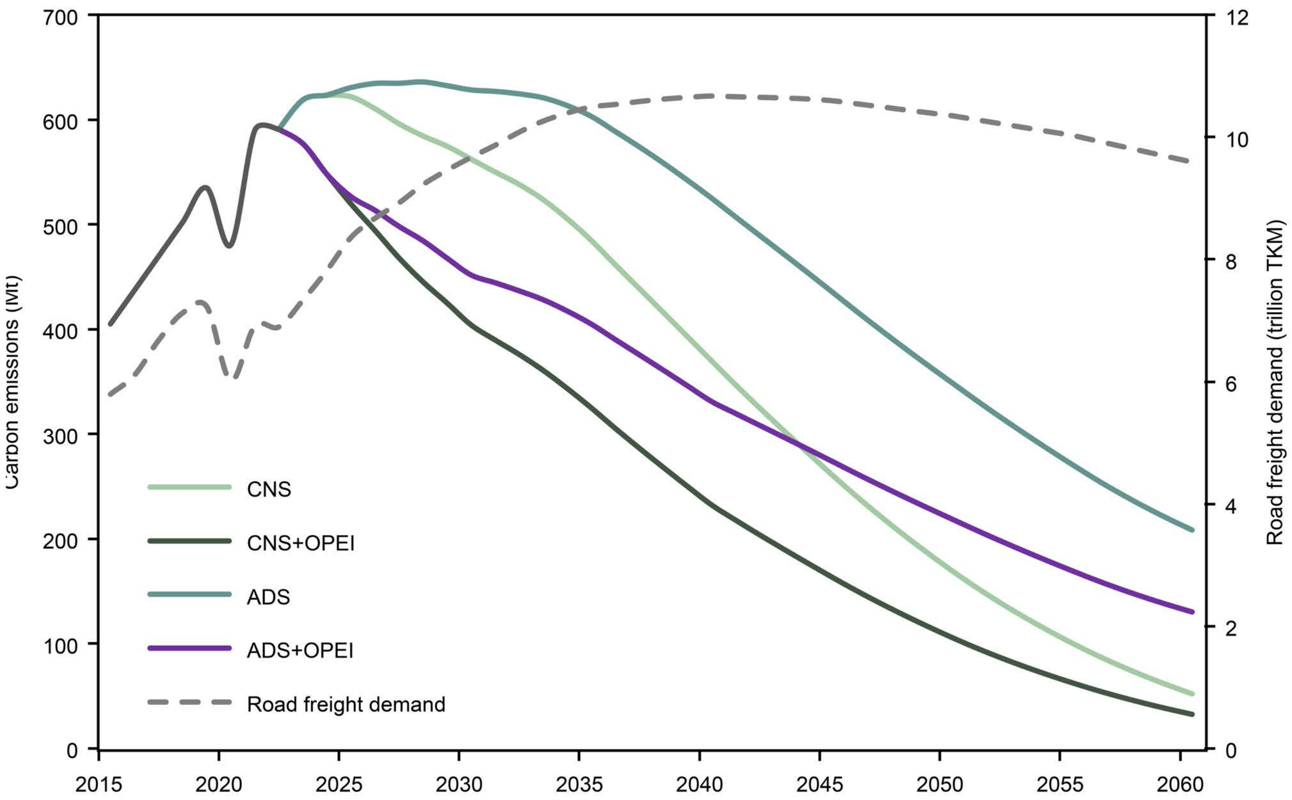
To explore the potential near- and long-term energy and climate implications of operational efficiency improvement via freight digitalization, future scenarios are constructed using a technology-rich transport-energy model for China's road freight sector (see the Methods section for a detailed description). Figure 4 compares several emission scenarios in consideration of China's announced policy targets to peak total carbon emissions by 2030 and to achieve carbon neutrality by 2060. Given China's climate pledge, total emissions from the trucking sector are expected to peak around 2030, although road freight tkm will not reach its highest level until around 2040. The carbon neutrality scenario (CNS) relies on the massive deployment of zero-emission technologies such as battery electric and hydrogen fuel-cell vehicles to

Figure 3. Intertemporal and cross-country comparisons of vehicle empty running and capacity utilization for regional and long-haul trips. a, Comparisons of vehicle empty running and capacity utilization between the 2018 sample and 2021 national averages in China. 2021 data are based on big data collected from on-vehicle IoT devices and reported in TUC Intelligence (2022a). Unlike the 2018 sample, 2021 data are calculated as the percentages of empty/fully laden operating hours rather than the percentages of empty/fully laden mileages. However, it is assumed here that these two methods produce similar estimates and hence are used for comparison. **b,** Comparisons of vehicle empty running for regional and long-haul trucking in China, the US, and the EU. Note that considering geographic differences, empty-running miles data for international trips are displayed for EU countries, whereas national averages are reported for the US and China. Data for EU countries are from EUROSTAT (2022). Data for the US are the average value of for-hire fleets and are reported by ATRI (2021).



achieve the 2060 target. However, the large-scale adoption of these new technologies for heavy freight trucks will not accelerate until after 2040, and before that, their degree of penetration is expected to remain limited. In comparison, operational efficiency improvement (OPEI) measures are expected to take effect more rapidly and bend the emission curve much earlier on (CNS+OPEI scenario) given their fast market uptake, with potential near-term mitigation effects outweighing those of zero-emission technologies (comparing the ADS+OPEI and CNS scenarios). Emission reduction via freight digitalization is due primarily to the reduced number of vehicle activities as a result of a higher average load factor, as less motorized travel is required and, hence, less CO_2 is emitted. Overall, a combination of zero-emission technology adoptions in the long term and operational efficiency improvement in the near term yields the best mitigation effects (CNS+OPEI scenario).

Figure 4. Comparison of China's road freight transport emission scenarios up until 2060. CNS: Carbon neutrality scenario, a pathway to carbon neutrality in China's energy sector in which CO_2 emissions reach a peak before 2030 and fall to net zero by 2060, in line with China's stated goals. **ADS**: Active decarbonization scenario, a pathway that considers primarily announced policies for near-term targets but does not incorporate any potential future policy changes to meet the long-term 2060 goals. **OPEI**: Operational efficiency improvement. **CNS+OPEI**: A scenario that incorporates both policy measures under the carbon neutrality scenario and operational efficiency improvement measures. **ADS+OPEI**: A scenario that incorporates both policy measures under the active decarbonization scenario and operational efficiency improvement measures. See the Methods section for the model description and key scenario assumptions.



Discussion

Despite significant technological progress and fuel efficiency improvement, total energy consumption has continued to grow in many sectors (Tiefenbeck 2017), as demand for energy services has consistently outgrown its efficiency gains. The same situation has occurred in the transport sector (ITF 2019; Milovanoff, Posen, and MacLean 2020). Therefore, one of the keys to reducing carbon emissions is to take a behavioral approach and avoid excessive demand (Creutzig et al. 2022; Dietz et al. 2009). Behavioral intervention would be a necessary complement to low-carbon technologies since, without it, relying on technology alone could simply transfer emissions from the end-use stage to upstream processes such as energy production and conversion. Furthermore, while technological progress is a slow-acting, uncertain and costly long-term process, behavioral changes can take effect much more quickly and at lower cost, making it such changes a potential solution for emission mitigation in the near term (Dietz et al. 2009).

The rapid advances of information and communication technologies (ICT) in the last ten years have enabled new disruptive business models in the logistics sector (GeSI 2015; Malmodin and Bergmark 2015) and have introduced opportunities for behavioral intervention worldwide. By essentially compensating for the largely "missing" 3PL sector, the rapid development of freight digitalization in developing countries offers the potential to help their road freight sectors substantially improve operational efficiency and achieve economies of scale, thereby offering a feasible near-term pathway through which to achieve mitigation. The primary mechanism for emission reduction in the difficult-to-abate road freight sector is enabling market behavioral changes on both the demand and supply sides.

From the perspective of freight demand, in addition to replacing small and isolated physical freight markets with much larger national online freight platforms, by aggregating demand across geography, digitalization may substantially improve the predictability of freight flows between origin-destination location pairs, hence reducing regional imbalance and enabling the better planning of fleet operation (Zhu and Zhu 2022). This situation would facilitate a transformation from the volatile spot freight market to a much more stable contractual market, thus providing carriers with more predictability and allowing for the further optimization of their operations. Regarding this particular point, some online freight platforms have initiated this transition by starting dedicated freight line services based on the consolidation of spot shipping demands (CFLP 2019).

On the supply side, as owner-operators and small carriers make up the vast majority of the freight service supply in many low- and middle-income countries, freight digitalization offers a potential pathway through which to accelerate the consolidation of market supply and achieve reliable trucking capacity. Through the integration of fleet management functionalities, including real-time load tracking, route optimization and driver behavior monitoring, freight matching mobile applications could adjust trucker behavior and improve the productivity of owner-operators and small carriers to match the performance of large fleets (Chang'an University 2022; Zhu and Zhu 2022). In this regard, several digital freight-matching companies have gone a step further to stabilize service supply by creating their own fleets to accommodate shipper demands (SOHU 2018; Zhu and Zhu 2022)

Furthermore, from the perspective of policymakers, market consolidation as a result of freight digitalization may substantially facilitate the regulation of an otherwise highly fragmented and informal market. Policymakers could mandate vehicle efficiency improvements or provide driver training by coordinating with digital freight service providers. Moreover, governments could work with digital freight aggregators to improve the capacity for multimodal transport and accelerate the modal shift to rail and shipping (Xinhua Daily 2022). In contrast, digital freight aggregators could assist owner-operators and small carriers in adopting new vehicle technologies by providing support such as loans and other value-added services (cn156 2019).

While this research utilizes data from China's booming online freight-matching sector, freight digitalization has been growing rapidly in many other developing countries across Asia, the Middle East, Africa and South America (Air Cargo News 2019; DHL 2019, 2020; FreightWaves 2019a, 2019b; Jamal 2021; McKinsey & Company 2019, 2020; NDTA 2021; News24 2021; PYMNTS 2023; Reuters 2021). For instance, startup investment in freight digitalization saw a compound annual growth rate (CAGR) of 190% between 2014 and 2019 in India, another fast-growing road freight market (Deloitte 2019). While expecting high road freight activity growth in the coming decades, trucking sectors in these emerging markets are also plagued by low operational efficiencies due to similar issues witnessed in China's road freight market. In this regard, the rapid uptake of freight digitalization in these new markets has the potential to considerably improve operational efficiency and reduce vehicle emissions in the near term. For example, some research has estimated that optimized truck use could lead to an annual reduction of 185 million tonnes of CO_2 emissions in 2050 in India due to a significantly reduced number of annual vehicle kilometers (NITTI Aayog, RMI, and RMI India 2021). The reduced transport demand due to behavioral efficiency improvement could further amplify energy and carbon savings by lowering conversion losses at both the upstream resource-processing stage and the final service-delivery stage (IPCC 2023) in developing countries and lessen the burden of emission reduction on supply-side solutions while minimizing any associated risks and uncertainties (Grubler et al. 2018).

To fully utilize the digitalization strategy to achieve emission reduction, developing countries need to actively promote the digital transformation of their conventional road logistics sector. Governments may directly establish public online freight exchanges to facilitate the dissemination of information or engage the private sector to develop such digital platforms. New policy frameworks must also be created to encourage and regulate the development of the digital freight logistics industry. Additionally, policymakers may target market players to facilitate the adoption of larger-capacity and more efficient vehicles via policy measures such as introducing vehicle procurement financing to owner-operators and phasing out small and inefficient vehicles. Complementary infrastructure to support larger vehicles and corresponding regulations such as HDV fuel economy standards must also be developed accordingly. Furthermore, mobile network infrastructure, at least in major freight transport nodes, needs to be established to enable online freight matching.

In addition, several potential limitations of freight digitalization must also be noted. First, the proprietary truck operation data in this research focus predominantly on regional and long-haul deliveries, where the results suggest a significant reduction in vehicle empty-running time. For short-duty cycles such as urban deliveries, however, the percentage of unladen distance is shown to remain high, despite being digitally matched. While this finding is partly due to the particular nature of urban delivery, which differs significantly from long-distance trucking, it may also suggest possible limits of operational efficiency gains via digitalization for certain use cases. Under these circumstances, zero-emission vehicle technologies such as electrification technologies or alternative fuels could be an equally important near-term mitigation solution. In fact, in the carbon neutrality scenario in the analysis, it is assumed that rapid electrification will materialize for the light commercial vehicle segment in China, with an electrification rate surpassing 50% in the early 2030s. However, more research is needed to understand the impact of digitalization on urban freight transport, which is itself an important market segment that is currently undergoing rapid digital transformations in parallel to the long-haul full truckload market (McKinsey & Comany 2020).

Second, while digitalization has had much earlier and deeper penetration in the urban passenger mobility market than in other markets, its climate change mitigation effects remain hotly debated (IPCC 2022). Some research suggests that contrary to expectations, shared mobility via services from transportation network companies (TNCs), such as Uber and Lyft, actually leads to an increasing number of vehicle miles being traveled and increasing amount of road congestion with lowered levels of public transit ridership (Diao, Kong, and Zhao 2021; Henao and Marshall 2019). Hence, the key to digitalization being able to make a difference is to ultimately reduce the total number of vehicle kilometers traveled and replace motorized travel with less carbon-intensive transport options. Digitalization will have a positive climate change impact only when it is paired with a higher level of vehicle occupancy (Creutzig 2021).

Finally, although digitalization may significantly improve the systemic efficiency of road freight, policymakers should take precautions against potential negative outcomes, including rebound effects, substitution effects, and induced demand due to the relative productivity improvement of trucking compared to other transport modes. In the absence of sufficient alternative transport infrastructure (such as railways) and often lacking an integrated multimodal freight transport system, most low- and middle-income developing countries rely on road transport for domestic good shipment given its fast speed, cost effectiveness, less strict infrastructure requirements, and quality assurance (CATARC 2017, Chang'an University 2021; Mckinnon 2018; NITTI Aayog, RMI, and RMI India 2021). The fast-growing trend of online shopping and e-commerce worldwide in recent years, which accelerated during the COVID-19 pandemic (ITF 2021), has reinforced the demand for timely and flexible cargo delivery via road transport. Hence, in the event of road logistics efficiency improvement, developing countries will likely face strong rebound effects and additional induced demand for trucking since demand for freight services in these countries is far from saturation and an abundance of marginal consumers should exist (Sorrel, Dimitropoulos, and Sommerville 2009). Moreover, freight movement on other less-carbon-intensive modes, such as rail and shipping, may be substituted by roads due to their relative competitiveness. These undesirable outcomes may partially or even completely offset the positive climate benefits (as in the case of urban shared mobility) of the operational efficiency gains as a result of digitalization in road freight. Therefore, governments need to employ price policies (e.g., fuel tariffs and carbon taxes) or nonprice regulations to tackle these unintended behavioral responses and steer market behavior in a positive direction (Sorrel 2007; IPCC 2022). A comprehensive policy framework and a multimodal freight transport system need to be established to complement the rapid efficiency improvement in road logistics and offset any potential negative climate impact.

Methods

Transport-energy model. Road freight transport emissions are estimated using the activity-structure-intensity-fuel (ASIF) approach (Schipper et al. 2000), i.e., by multiplying road freight activities by energy intensity and carbon intensity for all vehicle and powertrain types to estimate total emissions. Three vehicle types (heavy freight trucks (HFTs), medium freight trucks (MFTs), and light commercial vehicles (LCVs)) and seven powertrain types (electric vehicles (*EVs)*, hydrogen fuel cell electric vehicles (*FCVs)*, hybrid vehicles (*HEVs)* fueled by gasoline, hybrid vehicles (*HEVs)* fueled by diesel, internal combustion engine vehicles (*ICEVs)* fueled by gasoline, internal combustion engine vehicles (*ICEVs)* fueled by diesel and natural gas vehicles (*NGVs*)) are considered for China's road freight market. Operational efficiency improvement effects are directly reflected by vehicle carrying capacity, capacity utilization and the average number of annual vehicle kilometers traveled.

Equation (3) describes the model:

$$EM = \sum_i \sum_j vkt_i * S_{ij} * FCR_{i,j} * F_j \quad (3),$$

where *EM* denotes the total road freight CO_2 emissions; *i* and *j* index vehicle type and powertrain type, respectively; *FCR* denotes fuel consumption per 100 km traveled; and *F* is fuel carbon intensity.

The total stock of each vehicle type is determined by its expected role in future domestic road freight systems and utilization at the individual vehicle level, as specified in equation (4):

$$S_i = \frac{TKM * SHARE_i}{vkt_i * CAP_i * USE_i} \quad (4).$$

where *SHARE* indicates the proportion of ton-km transported by each vehicle type in the future, *CAP is* the average available carrying capacity per vehicle, and *USE* is average degree of capacity utilization. The powertrain distribution within each vehicle type is then determined based on the vehicle survival curve and announced government sales targets for alternative-fuel vehicles.

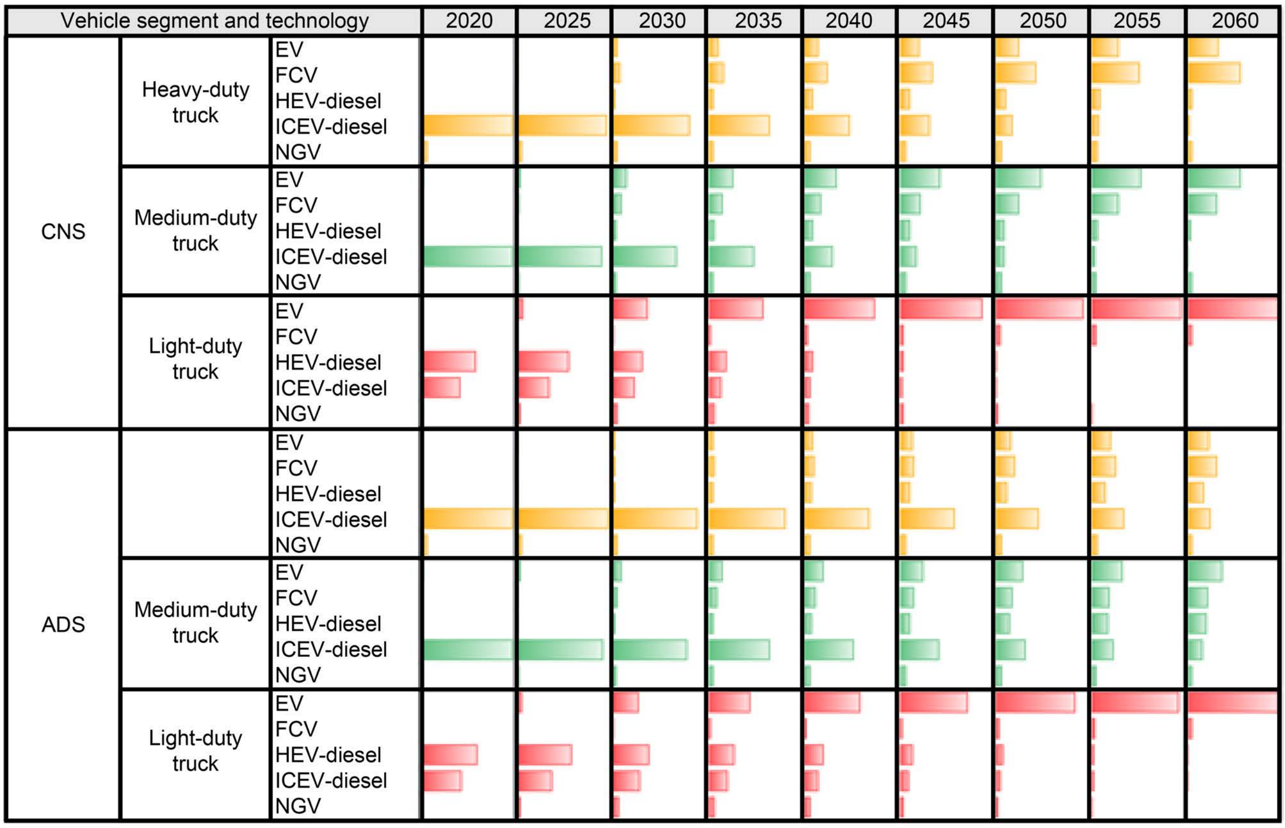
The model runs from 2015 to 2060. Historical data (2015-2021) on vehicle stock, road freight demand and its distribution across different vehicle types are sourced from the China Annual Statistical Database (NBS 2022) and IEA (2021). Data on the average number of annual vehicle kilometers traveled per vehicle and fuel consumption rate are from the China Automotive Technology & Research Center (CATARC 2022). Data on fuel carbon intensity are from the IPCC's Guidelines for National Greenhouse Gas Inventories (IPCC 2006). Data on truck carrying capacity and capacity utilization are from transport yearbooks (MOT 2022; Yearbook of China Transportation and Communications 2022) as well as previous studies (McKinsey & Company 2019; RMI 2016).

For future data input, information on road freight TKM is based on existing literature (Pan et al. 2018). The future evolution of the average number of annual vehicle kilometers traveled per vehicle, vehicle fuel consumption rate, capacity utilization level and vehicle powertrain structure are provided at a five-year interval, with annual numbers in between being linearly interpolated. The details are outlined in the scenario settings below. The average carrying capacity across vehicle types is assumed to stay constant.

Scenario settings. To investigate the potential near- and long-term implications of operational efficiency improvement while considering low-carbon technology adoption, several future scenarios are constructed for China's road freight sector. The active decarbonization scenario (ADS) depicts a technology-centric pathway that accounts for announced policies for near-term targets, such as commitments made in China's National Determined Contributions (NDCs), the New Energy Vehicle Industry Development Plan for 2021–2035 (State Council 2020), the Action Plan for Carbon Dioxide Peaking Before 2030 (State Council 2021), and the Energy Conservation and New Energy Vehicle Technology Roadmap 2.0 (**SAE-China 2020**), without factoring in operational efficiency improvement. The carbon neutrality scenario (CNS), in contrast, represents a pathway through which to achieve China's long-term commitment of achieving carbon neutrality by 2060 via the accelerated deployment of zero-emission vehicles such as battery electric and hydrogen fuel-cell trucks. Note that in this scenario, a small amount of emissions, mainly from long-distance road freight, will remain in 2060, which is expected to be offset by carbon capture, utilization and storage (CCUS) from other sectors such as industry.

The impacts of operational efficiency improvement (OPEI) are measured in combination with the technology adoptions in two integrated scenarios, namely, the ADS+OPEI and CNS+OPEI scenarios. Figures 5 and 6 display detailed powertrain penetration and operational efficiency evolution information across vehicle types, respectively. Note that as the vehicle load increases, the fuel consumption rate is expected to rise. Moreover, an increase in the number of annual vehicle miles would accelerate turnover of vehicle stock and expedite the introduction of vehicles that are more energy efficient, assuming that the expected number of vehicle lifetime miles stay unchanged. The net

Figure 5. Evolution of freight vehicle powertrain technology under different scenarios. Length represents the proportion of vehicle technology penetration.



impact of these two opposing effects as a result of operational efficiency change is likely small in comparison to other OPEI effects, e.g., reduced vehicle travel due to an increase in the load factor. Hence, it is assumed in this analysis that these two opposing effects completely offset each other and have zero impact on energy consumption and carbon emissions.

Vehicle operation data. Proprietary vehicle operation data are sourced from China's fast-growing digital freight-matching industry. Trip information from 2,000 active trucks is collected for the period October 1–November 22, 2018, containing a total of 51,021 consecutive road freight trips. Detailed information includes trip characteristics such as origin and destination locations and vehicle and cargo attributes, including vehicle type, carrying capacity, and cargo weight. The recorded trips cover all 31 provinces and municipalities of Mainland China. The proportions of intracity, intercity and intraprovince, and interprovince trips are 4%, 23%, and 73%, respectively. Empty running is defined as the truck distance driven between the destination of the previous trip and the origin of the current trip. Accordingly, the share of empty miles is then calculated as its percentage of the total distance.

Figure 6. Evolution of freight vehicle capacity utilization and load factor under different scenarios.

	Scenario	Vehicle type	2020	2021	2025	2030	2035	2040	2045	2050	2055	2060
Capacity utilization (%)	ADS/CNS	Heavy-duty truck	40%	42%	52%	52%	52%	52%	52%	52%	52%	52%
		Medium-duty truck	50%	52%	70%	70%	70%	70%	70%	70%	70%	70%
		Light-duty truck	40%	45%	58%	58%	58%	58%	58%	58%	58%	58%
	ADS/CNS +OPEI	Heavy-duty truck	40%	42%	62%	75%	80%	85%	85%	85%	85%	85%
		Medium-duty truck	50%	52%	70%	75%	80%	85%	85%	85%	85%	85%
		Light-duty truck	40%	45%	70%	75%	80%	85%	85%	85%	85%	85%
Load factor (tonne)	ADS/CNS	Heavy-duty truck	12.0	12.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
		Medium-duty truck	5.0	5.2	6.2	7.0	7.0	7.0	7.0	7.0	7.0	7.0
		Light-duty truck	0.8	0.9	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	ADS/CNS +OPEI	Heavy-duty truck	12.0	12.6	18.6	22.5	24.0	25.5	25.5	25.5	25.5	25.5
		Medium-duty truck	5.0	5.2	7.0	7.5	8.0	8.5	8.5	8.5	8.5	8.5
		Light-duty truck	0.8	0.9	1.4	1.5	1.6	1.7	1.7	1.7	1.7	1.7

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About the Project

China has witnessed substantial freight transport energy consumption growth in the past 20 years, and it is expected to continue to be a significant contributor to global transport oil demand in the coming decades. With China being the top buyer of petroleum products from Saudi Arabia, this project seeks to use state-of-the-art modeling approaches and data to develop a next generation freight transport energy demand model in order to understand the latest trends in China's freight transport oil demand.

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