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Nature Communications

https://doi.org/10.1038/s41467-026-71160-1

Article in Press

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Received: 15 September 2024

Accepted: 12 March 2026

[redacted]

Cite this article as: Xu, X., Ou, S., Peng, T. *et al.* The potential role of truck-hailing and operational efficiency improvement in China’s road freight decarbonization. *Nat Commun* (2026). https://doi.org/10.1038/s41467-026-71160-1

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The potential role of truck-hailing and operational efficiency improvement in China's road freight decarbonization

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Abstract

Truck-hailing is an emerging business model that could potentially transform the road freight sector. As a new form of horizontal collaborative transport, it offers great potential to improve operational efficiency—an important yet underrepresented demand-side strategy in current transport decarbonization research. Drawing on a proprietary national truck-hailing dataset (N=51,021) and an enhanced vehicle fleet model that incorporates operational factors, here we assess the potential carbon emission impacts of truck-hailing and operational efficiency improvements in China under multiple scenarios. Under medium projections, enhancements in load factor and reductions in empty running could cut China's road freight emissions by 886-2203 Mt (9%-24%) in the near term (2020–2035) and 2504-3327 Mt (23%-31%) in the long term (2035–2060), compared to a business-as-usual pathway. However, capacity constraints of zero-emission vehicles may reduce these benefits, resulting in roughly 3% higher emissions in the near term and nearly 10% in the long term.

Introduction

Truck-hailing, or digital freight matching, is an emerging business model that could potentially transform the road freight sector[1-6]. As part of the broader digitalization and sharing economy megatrends[7], this cloud-based logistics service primarily caters to the spot (non-contractual) road freight market by matching shipper demand with carrier supply via mobile apps[8-10]. In addition to load matching, truck-hailing platforms often feature route optimization and real-time load tracking, similar to a fleet or transportation management system[11](Fig. 1). Since its inception, truck-hailing has gained rapid market traction across developed economies, including the United States and Europe[8,10]. In China—the world's largest road freight market by tonne-kilometer—it has also experienced strong growth since its emergence in 2013[12], reaching an estimated 22% penetration at present (methods). According to the latest statistics, there were over 130 million truck-hailing journeys in 2023, fulfilled by more than 7.99 million trucks—equivalent to almost 70% of China's commercial trucks fleet[4] (Supplementary Fig. 1).

<Insert Figure 1>

Globally, road freight transport is a major driver of rising energy consumption and carbon emissions, fueled by rapidly expanding road freight activities that are projected to more than double by 2050[1,13]. Trucking could potentially surpass passenger vehicles as the largest oil consuming sector, as demand growth offsets anticipated efficiency gains while large-scale deployment of low-carbon technologies remains in its early stages[2,14]. Although most existing decarbonization strategies in this sector have focused on enhancing vehicle efficiency and adopting low-carbon fuels, there has been comparatively limited attention to mitigating emissions from a logistics or service delivery perspective [2,15]. Notably, Chapter 5 of the Sixth IPCC Assessment Report highlights service delivery efficiency improvements at the end-use phase as a critical demand-side mitigation strategy for transport and other sectors[7]. According to the International Transport Forum, logistics and supply chain optimization could potentially deliver 30-50% reductions in road freight emissions[2], largely through operational efficiency improvements—such as increased vehicle utilization—enabled by new information and communication technologies[1-2,15-16].

Leveraging the latest mobile internet technologies, truck-hailing essentially represents a new iteration of horizontal collaborative transport solutions[5,8], which is recognized as one of the most effective methods for enhancing operational efficiency and sustainability in freight transport[9,17-20]. Horizontal collaboration refers to cooperation among logistics players at the same level of the supply chain, and has been extensively studied in operational research and logistics literature[9,20-21]. Compared to conventional non-collaborative transport, existing research indicates that horizontal collaborative solutions have the potential to substantially improve trucking efficiency—especially for small carriers—by reducing empty hauling, improving load factor (or payload capacity utilization), cutting down unnecessary travel, and decreasing fleet size via asset sharing and route optimization[6,8-9,18-19,21-35]. Likewise, recent research on China's emerging digital freight platforms has found that, relative to traditional analogue and fragmented (non-collaborative) freight forwarding business model, truck-hailing services facilitate better load-matching and boost revenue-generating mileage for carriers by expediting turnaround and minimizing empty journeys[12,36] (Supplementary note 1).

While most existing studies have investigated the efficiency impact of horizontal collaborative transport and digital freight matching using small samples or simulations at the micro level, there remains a gap in understanding how increasing digitalization of road freight—and operational efficiency gains of trucking as a potential result—could shape sectoral carbon emissions and impact national decarbonization pathways. Among the existing research is this aspect, McKinnon (2018) notes that reducing empty running, improving load factor, and utilizing high-capacity vehicles each contributes to lowering road freight emissions[15]. Mulholland et al. (2018) estimate that combined measures of road freight operational and logistics improvements could lead to around 30% cumulative GHG emissions reduction in 2050 compared to the reference case[37]. Khanna et al. (2021) and Wang et al. (2022) identify freight vehicle operational and logistics improvement as a viable strategy to decarbonize China's HDV sector[38-39], while Xue and Liu (2022) highlight that increases in vehicle occupancy (average load per truck) offer high potential for near-term decarbonization in China's road freight sector[40]. Nevertheless, many of these studies have based their analyses on assumed logistics improvements, underscoring the need for more robust empirical evidence. Moreover, existing research is limited by methodological gaps that precludes a comprehensive account of important operational efficiency factors.

In this study, we begin to address these research gaps, utilizing recent empirical data and an enhanced modeling approach to explore the potential macro-level emission implications of truck-hailing and operational efficiency improvements. We draw on a high-resolution national truck-hailing sample from China, featuring predominantly long-haul journeys undertaken by medium- and heavy-duty trucks (MHDTs). China is the world's second largest road freight CO_2 emitting country, with its freight vehicles accounting for 25% of global road freight emission growth between 2000 and 2015[1]. However, despite China's rapidly expanding road freight demand, operational efficiency in its trucking sector remains relatively low compared to that of many developed economies (Supplementary Table 1, Supplementary Fig.-11 and Supplementary note 1). As the Chinese government pledges to strengthen the logistics system as a key strategy to achieve peak economy-wide carbon emissions before 2030[41], it is crucial to understand how truck-hailing and operational efficiency improvements can help advance decarbonization in this sector, given the rapid uptake of road freight digitalization.

We analyze several key operational efficiency indicators—namely vehicle empty running, load factor, vehicle kilometers travelled (VKT)—which are key determinants of freight transport energy consumption and carbon emissions. While most freight transport models in existing transport decarbonization research and Integrated Assessment Modeling frameworks do not explicitly account for all of these parameters, here we developed an enhanced vehicle fleet model to incorporate these factors, and utilized multiple scenarios to explore how different trajectories of digital freight penetration and operational efficiency gains at the sectoral level may shape the overall road freight decarbonization pathway. Meanwhile, as China accelerates the adoption of zero-emission vehicles (ZEVs) to curb sector emissions[41], we examine a critical yet often overlooked issue—the impact of ZEV operational limitations on decarbonization pathways that prioritize large-scale ZEV deployment. Specifically, we assess how constraints in ZEV performance—such as reduced payload capacity and driving range, increasingly highlighted in recent studies[42-48]—may diminish their potential emission reduction benefits.

Our analysis, comparing against a baseline scenario, reveals great potential for reducing China's road freight emissions through a combination of logistics optimization and low-carbon technology adoption. Under medium projections, operational and logistical enhancements could yield cumulative emission reductions of 886-2203 MT (9%-24%) from 2020 to 2035 (near term) and 2504-3327 MT (23%-31%) from 2035 to 2060 (long term). Optimistic scenarios project even greater reductions, reaching 1880-3014 MT (20%-32%) and 3505-3543 MT (32%-33%) for the respective periods. These findings highlight a synergistic relationship between logistics optimization and technological advancements across both timeframes. Improved logistics offers near-term decarbonization opportunities, and can also lessen the long-term investment for low-carbon technologies and infrastructure by minimizing unnecessary travel. Our results indicate that combined operational and technological measures could decrease the total vehicle stock by over two-thirds by 2060, compared to relying solely on low-carbon technologies. Meanwhile, the operational limitations of ZEVs, particularly in payload capacity, are projected to have negative emission impacts of approximately 3% in the near-term and nearly 10% in the long-term.

Results

Truck-hailing services have achieved rapid development in China's long-haul and urban freight markets during recent years, primarily serving owner-operators who constitute the vast majority of road freight carriers and HDT stock in the country (Supplementary Note 1). Employment surveys conducted by the China Federation of Logistics & Purchasing indicate that online freight matching has gradually surpassed traditional offline freight brokers as a more important load source for truck drivers in China in the last few years[49-51]. The proprietary truck-hailing sample analyzed in this study focuses on the long-haul freight sector, encompassing 51,021 digitally matched, single origin-destination journeys completed mainly by MHDTs in late 2018. These journeys span all administrative regions (provinces and municipalities) and public road categories in mainland China (Supplementary Fig. 2). All carriers in the sample are full-time owner-operators who exclusively source their loads from freight-matching platforms during the sample period. The dataset integrates waybill, geospatial, and vehicle operation data from freight journeys. This synthesis allows for the calculation of key operational performance metrics and provides the foundation for subsequent in-depth modeling analysis (Methods).

<Insert Figure 2>

Fig. 2 presents the patterns of load-to-vehicle and journey-to-vehicle matching within the sample. Overall, there is a relatively good fit between cargo weight and vehicle capacity (Fig. 2a). As cargo weight increases, vehicles with larger payload capacity, especially tractor-trailers, are more frequently utilized for delivery. The proximity of the medium values to the 45-degree dashed line suggests that online matching has enabled many vehicles to achieve near-full capacity utilization. However, the figure also suggests that overloading remains common in China, due to low barriers to freight market entry, intense competition among owner-operators that account for majority of the MHDT carriers and vehicle stock, and the resulting low profit margins[11,52-53].

Regarding journey-to-vehicle matching, there are not many visible differences in usage profiles across vehicles with varying payload capacities (Fig. 2b). Smaller capacity vehicles, such as medium freight trucks (MFTs), are extensively used for long-distance inter-city and inter-province journeys. This is notable given that heavy freight trucks (HFTs), such as tractor-trailers, are generally considered more energy-efficient for long-haul applications due to their large payload capacity[54]. This may reflect owner-operators' limited ability to invest in the most energy-efficient vehicles for cargo delivery, as well as shippers' challenges in consolidating loads to maximize vehicle capacity utilization.

<Insert Table 1>

<Insert Table 2>

<Insert Table 3>

Table 1 shows the proportion of vehicle empty running mileages for both intra- and inter-province journeys within the sample. So far, research on truck travel behavior concerning empty mileage in China remains very limited. One commonly cited figure places this at approximately 40%[11,52,40,59]. For comparative purposes, we also present estimates derived from China's 2014 tolled expressway statistics[60] (see Supplementary Note 2 for more discussion on the comparison). Two observations emerge from Table 1. First, inter-province trips consistently exhibit lower percentages of empty miles compared to intra-province journeys. This disparity is likely due to the high opportunity costs associated with empty running during long-distance multi-province travel. Second, while the expressway data indicates that HFTs have less empty running than MFTs, the truck-hailing sample shows virtually no differences between these vehicle groups. This could be attributed to route optimization inherent in truck-hailing services.

Overall, the sample results reveal substantially lower levels of empty running than the expressway data. The empty running ratio observed in our sample approaches the efficiency levels reported in the China Federation of Logistics & Purchasing's 2021 survey of key commercial fleet, which record approximately 10% of empty running[61]. Our estimates are also closely aligned with figured reported by several EU countries—such as Portugal, Finland, Spain, Hungary, Greece, Denmark, and Belgium—where empty running ratios for comparable international journeys range from 6.5% to 10.8%, and with the EU-27 average of 12.2% in 2018[62]. Meanwhile, the tolled expressway statistics may underestimate the actual share of vehicle empty miles for several reasons. Primarily, they do not fully capture the entirety of trips, excluding segments such as the first- and last-mile that occur off tolled roads. Additionally, China's high toll charges make empty running on expressways prohibitively expensive[52]. In fact, our sample indicates truck drivers frequently opt for toll-free national and provincial highways, even when expressways offer much shorter routes. Furthermore, the expressway statistics may predominantly reflect the travel behaviors of large commercial fleets or those engaged in contract logistics, which typically face stricter time constraints and have healthier profit margins, as owner-operators are often deterred from using toll roads by high costs[50]. Recent GPS data from millions of commercial trucks indicate that, in 2021, the average percentage of empty running was 34%-36% for straight and dump trucks and 27% for tractor-trailers in China[51]. Hence, the actual share of truck empty mileage in China may still hover around 30% or higher.

Table 2 presents the vehicle load factor observed within our sample. Data regarding China's truck load factor are scarce. For comparison analysis, we include estimates derived from mean vehicle loads reported for various vehicle types in China's 2010 tolled expressway statistics, the last year such data was publicly available[63]. In the truck-hailing sample, the load factor for MFTs and HFTs are remarkably similar, both approaching 90%. This consistency reflects the efficient load-vehicle matching process. On the other hand, while HFTs exhibit comparable load factor across both datasets, MFTs again underperform HFTs in the expressway data. It is important to note, however, that the load factor values extrapolated from expressway statistics may overestimate average utilization and again are more likely to reflect the capacity utilization among vehicles engaged in contract logistics. This potential overestimation stems from the same factor that discourages empty running: high toll charges disincentivize inefficient use of vehicle capacity and discourage low-margin trips by owner-operators.

Next, we examine daily VKT levels within our sample and compare them to various external sources. The VKT values presented in Table 3 exhibit a wide range. Notably, the estimates derived from the truck-hailing sample align most closely with those from the 2017 truck-hailing pilot project, but considerably exceed values reported by all other sources. It is important to note that the comparative external data sources provide average VKT values that do not distinguish between large and small carriers. In contrast, our truck-hailing sample specifically focuses on small carriers, particularly owner-operators, which introduces a potential disparity in direct comparison. Logistics service provider G7, based on digital travel records from over half a million trucks in China, reports average daily VKT of 500km for large commercial carriers (fleets of 5-500 vehicles) and approximately 250km for small carriers/owner operators (fleets of fewer than 5 vehicles)[64]. These G7 figures correspond reasonably well with the daily VKT estimates shown in Table 3, suggesting that the mileage performance of owner-operators in our truck-hailing sample approaches that of large commercial fleets. Meanwhile, other reported values, such as those by Ministry of Transport (MOT) and the China Automotive Technology and Research Center (CATARC), may more accurately represent the daily mileage of small carriers/owner operators who primarily rely on traditional load-searching methods.

In summary, we observed substantially higher operational efficiency in the truck-hailing sample, aligning with findings reported in the existing literature. Given that improvements in operational efficiency can directly and indirectly reduce energy consumption and carbon emissions, their adoption at the road freight systemic level holds substantial implications for the sector's decarbonization pathway, should truck-hailing services maintain its current growth trajectory and achieve greater market penetration. Therefore, in the following sections, we model the future development of truck-hailing services and the operational efficiencies of MHDTs. We then explore the resulting implications for China's road freight transport decarbonization pathway. To accomplish this, we utilize the findings from our sample analysis and employ an enhanced vehicle fleet model that incorporates key operational efficiency factors, including empty running, load factor, payload capacity and VKT (methods).

Cross-cutting scenarios for logistics & technological improvement

To explore future possibilities for truck-hailing adoption and operational efficiency development in China's MHDT sector, we constructed five scenarios. The first, a business-as-usual (BaU) scenario, maintains the current truck-hailing penetration rate. The second and third scenarios present "optimistic" projections, anticipating rapid growth of China's truck-hailing market coupled with consistent improvements in average truck operational efficiency. These scenarios model freight digitalization following a linear and an s-shaped growth pattern, respectively, both reaching defined saturation levels (Supplementary Fig. 5). The fourth and fifth "medium" scenarios also project continued growth in freight digitalization and efficiency gains, but at approximately half the rate of the optimistic scenarios, acknowledging real-world challenges to market uptake and the slow operational efficiency improvements observed in developed digital freight markets[2,9,19,21]. Supplementary Fig. 7 illustrates the projected future trends for key operational efficiency indicators for both MFT and HFT across the five scenarios, using the truck-hailing sample's values as target levels at market saturation.

Recognizing China's commitment to decarbonize its road transport sector through low-carbon and fuel-efficient technologies, we also developed two scenarios along the technological dimension. The current policy scenario (CPS) projects the continuation of existing transport and energy policy initiatives. Conversely, the carbon neutrality scenario (CNS) envisions a more aggressive decarbonization path, characterized by the accelerated deployment of ZEVs, including battery electric and hydrogen fuel cell vehicles. Combining these logistical and technological changes, we established ten comprehensive cross-cutting scenarios (Fig. 3). The current policy – business as usual scenario (CPS_BaU) serves as the baseline for comparison. Detailed scenario parameters and methodologies are provided in the methods section.

<Insert Figure 3>

<Insert Figure 4>

Road freight transport decarbonization pathways along logistics and technological dimensions

Fig. 4a and 4b illustrate projected CO2 emission trajectories for China's MHDT sector, comparing BaU scenarios with medium and optimistic scenarios, respectively. Although road freight transport demand is expected to peak around 2040, CO2 emissions are projected to peak much earlier, by 2031, due to increasing adoption of low-carbon and fuel-efficient technologies. Both technological advancement and logistics improvements demonstrably contribute to this trend. Relying solely on accelerated technology deployment, without further operational and logistics improvements, would advance the emission peak to 2028, followed by a rapid decline (CNS_BaU). Integrating technology with logistics measures would further accelerate the peak, with the timing dependent on truck-hailing service and operational efficiency growth. In medium scenarios (Fig. 4a), the MHDT sector's emissions peak by 2022 (CNS_S-shape_Med) and 2025 (CNS_Linear_Med), while in optimistic scenarios (Fig. 4b), the peak occurs by 2020 (CNS_S-shape_Opt) and 2024 (CNS_Linear_Opt).

Logistics improvement considerably contribute to emission reduction, particularly in the near term. Enhanced load factor and vehicle empty running lead to lower travel demand and a much smaller vehicle stock (Supplementary Fig. 8). For example, under the CPS_linear_Opt scenario, if China's average vehicle empty running and annual VKT reach current U.S. levels by 2030 (around 20% and 90,000km, respectively), the MHDT vehicle stock would decrease by over a third compared to 2020. The near-term decarbonization impact of logistics improvements, relative to rapid low-carbon technology adoption, is highlighted by the shaded areas in Fig. 4a and 4b. Compared to the CNS_BaU scenario, which assumes no logistics improvements, rapid operational efficiency gains result in additional cumulative CO2 emission reductions of 2547 Mt (CPS_S-shape_Med) and 476 Mt (CPS_Linear_Med) in the medium scenarios, and 3593 MT (CPS_S-shape_Opt) and 2398 (CPS_Linear_Opt) in the optimistic scenarios, before low-carbon technologies become the primary driver of emission reduction.

<Insert Figure 5>

<Insert Figure 6>

Synergies between logistics and technological improvements across varying timeframes

Fig. 5 analyzes the contributions of various factors to emission reductions in year-over-year comparison within each scenario using the LMDI approach (methods), examining both the near-term (2020-2035) and long-term (2035-2060) changes. Eight driving forces are considered: operation and logistics (empty running, load factor, payload capacity, VKT), technological factors (fuel efficiency, low-carbon fuels), and other factors (demand, vehicle structure) (see methods). In the baseline scenario (CPS_BaU), current policies, primarily focused on near-term targets, are insufficient for sustained decarbonization after 2035, resulting in substantial residual emissions in the MHDT sector in 2060 (Fig. 5a). Aggressive deployment of low-carbon technologies substantially reduces emissions, mainly in the long-term as technology adoptions accelerates (Fig. 5b). Conversely, while technological improvement (fuel economy improvement and low-carbon fuel adoption) have limited near-term impact, operational and logistics enhancements offer substantial near-term emissions reduction potential, driven by rapid growth of truck hailing services, complementing technology's role (Fig 5c, 5e, 5g and 5i).

With combined logistics and technology strategies, logistics yields the most immediate emission reductions, but technology's impact becomes dominant in the longer run (Fig. 5d, 5f, 5h and 5j). However, compared to the baseline scenario (CPS_BaU), logistics plays an equally important role in long-term cumulative emission reductions (Fig. 6). This is because near-term reductions in unnecessary travel, due to improved operational efficiencies (better load factor and lower empty running), lessen the need for extensive ZEV deployment in the long run. The greater cumulative emission reduction achieved through logistics improvements, compared to technological advancements across both timeframes, highlights another potential synergy between the two decarbonization forces. Near-term operational and logistics efficiency improvements could reduce the long-term mitigation costs associated with low-carbon technologies and infrastructure. This is reflected by the vehicle stock in the CNS_Linear and CNS_S-shape scenarios being reduced to less than one third of the CNS_BaU scenario by 2060 in both medium and optimistic projections (Supplementary Fig. 8).

<Insert Figure 7>

The impact of operational performance limitations of ZEVs

Current medium- and heavy-duty ZEVs, such as battery electric trucks, often face limitations in range and payload capacity[42]. This is supported by recent statistics from China, which indicates that electric and fuel cell trucks exhibit lower range and payload performance compared to internal combustion engine (ICE) vehicles[65-66]. Consequently, our analysis incorporates the assumption that ZEVs initially possess reduced range and capacity compared to ICE vehicles, with these performance gaps gradually diminishing over the model period (methods). The impact of ZEVs' operational limitations, coupled with the structural shift towards electric and fuel cell powertrains, is not directly illustrated in Fig. 5, but is evident in Supplementary Fig. 9. Since the average ZEV with performance limitations cannot achieve one-on-one replacement with their ICE counterparts[43], accelerated adoption of low-carbon technologies in the CNS scenarios results in lower average vehicle occupancy (tonnes per vehicle) compared to all CPS scenarios. In the post-2035 period under optimistic projections, average vehicle occupancy also declines because the decrease in average payload capacity outweighs the gains in load factor. As a result, additional vehicle travel is required across all powertrains to meet the same aggregate demand in TKM, leading to increased use of diesel, hybrid and NG vehicles (Supplementary Fig. 10) and higher tailpipe emissions.

Fig. 7 presents the emission results from counterfactual experiments, assuming no range and capacity limitations for EVs and FCVs. These results suggest that ZEV performance penalties can lead to higher cumulative emissions in both near- and long-term. Specifically, in the CNS scenarios with accelerated low-carbon technology deployment, cumulative carbon emissions are approximately 3% higher from 2020-2035 and 10% higher from 2035-2060 compared to scenarios without range and capacity penalties. The increase in emissions is primarily attributed to greater vehicle travel resulting from reduced average loads due to decreased payload capacity. Conversely, the range limitation is offset by an increase in vehicle stock and does not directly affect aggregate TVKT or total carbon emissions, once other operational efficiency parameters are considered.

Discussion

China's truck-hailing services have experienced remarkable growth in the past decade. With a 94% average annual growth in digitally matched journeys from 2020 to 2023 (Supplementary Fig. 1), the new business model could potentially transform China's highly fragmented road freight sector, dominated by small carriers and owner-operators. Given China's status as the world's largest vehicle market and a major transport emitter, understanding the impact of this new freight digitalization trend could be critical for achieving the country's national decarbonization targets.

Leveraging a national truck-hailing sample, we observed strong operational efficiency performances of vehicles using these services, which is consistent with findings from existing literature. We then developed an enhanced vehicle fleet model to assess the potential of operational efficiency and logistics improvements in near- and long-term decarbonization pathways for China's road freight transport sector, considering the nation's ambitious low-carbon technology deployment targets. Compared to a baseline scenario, we project that operational and logistics enhancements could potentially reduce China's road freight emissions by 886-2203 Mt in medium scenarios and 1880-3014 Mt in optimistic scenarios between 2020 and 2035 (Fig. 6). This highlights their crucial role in near-term decarbonization, complementing technological advancements. Furthermore, improved logistics, by minimizing unnecessary travel, could considerably reduce the long-term need for low-carbon technology investment, potentially decreasing vehicle stock by more than two thirds in 2060. Meanwhile, capacity constraints of zero-emission vehicles may reduce these benefits, resulting in roughly 3% higher emissions in the near term and nearly 10% in the long term.

Several limitations of this study need to be noted. First, our analysis focuses solely on operational efficiency improvements among owner-operators, who currently represent the majority of carriers and vehicle stock in China, while excluding the emission impacts of freight digitalization in larger commercial fleets. Additionally, our analysis is restricted to long-haul road freight, leaving urban freight delivery unexplored. Therefore, further research is needed to fully evaluate the emission impact of freight digitalization across all stakeholders and market segments in the road freight sector. Second, while digital freight services offer potential improvements in road freight logistics efficiencies, policymakers must consider possible behavioral responses like rebound effects, substitution effects, and induced demand, similar to those observed in ride-hailing[7,16,67-70]. Given that China's road freight sector handled over 75% of domestic freight tonnages from 2000 to 2020[71] and has seen a shift from rail to trucking[40,72], efficiency gains in trucking could lead to strong rebound effects and increased road freight demand. This could also result in further substitution of less carbon-intensive modes such as rail and shipping, thereby diminishing the emission reductions from improved trucking efficiency. While increased demand for road freight services may yield economic and social benefits, policymakers must consider the unintended behavioral consequences from a climate policy perspective and respond accordingly[53,73] to effectively achieve decarbonization targets.

Third, our model did not consider any indirect effects of operational efficiency and logistics enhancements. These may include reduced congestion, increased travel speed, and shorter travel distance due to a smaller vehicle fleet. Additionally, increased VKT and potential profitability gains, or reduced total cost of ownership (TCO) might incentivize fleet operators and small carriers to adopt ZEVs and improve vehicle energy efficiency[11,43,74-75]. A smaller vehicle fleet could also greatly lower the required investment in clean energy infrastructure. Finally, the expansion of truck-hailing services may have substantial social and economic implications beyond carbon emissions. Our analysis indicated that demand reduction through logistics improvements and subsequent fleet reduction could potentially pose employment risks for stakeholders such as owner-operators. Understanding these broader welfare impacts is crucial but beyond the scope of the current study, presenting a valuable venue for future research.

Methods

Truck-hailing sample. Proprietary vehicle trip data were obtained from China's leading truck-hailing service providers. The dataset includes trip records from 2000 active vehicles operated by owner-operators who exclusively use digital freight platforms to source freight. These data cover the period from October 1 to November 22, 2018, and contain a total of 51021 consecutive road freight trips, reconstructed from millions of GPS location records. All digitally matched trips are single origin-destination (OD) journeys, and do not include multi-stop journeys that involve multiple origins and destinations.

The dataset combines waybill, geospatial, and vehicle operation information. It contains key trip characteristics such as OD locations, and distances of laden and unladen/empty journeys. It also covers vehicle and cargo attributes, including vehicle type, payload capacity, and cargo weight. The trips span all regions of mainland China, encompassing 31 provinces and municipalities (Supplementary Fig. 2), and cover all major public road types—expressways (tolled), national and provincial highways, and other public roads. Supplementary Table 3 presents a breakdown of trips by duty cycle.

In this study, vehicle empty running is defined as the distance traveled between the destination of one trip and the origin of the subsequent trip, as illustrated in Supplementary Fig. 3. The share of empty miles is calculated as the percentage of this distance relative to the total travel distance.

Enhanced vehicle fleet model. Carbon emissions from road freight transport are estimated using the transport activity – modal structure – energy intensity – fuel to carbon ratio approach[37], as shown in Equation (1) below, where total emissions from the medium- and heavy-duty sector are calculated as the sum of emissions across vehicle and powertrain types. This study considers two vehicle types—medium freight truck (MFT) and heavy freight truck (HFT)—and five powertrain types: electric vehicle (EV), hydrogen fuel cell electric vehicle (FCV), hybrid vehicle powered by diesel (HEV-diesel), diesel-fueled internal combustion engine vehicle (ICEV-diesel) and natural gas vehicle (NGV). Other low-carbon fuel options, such as biofuels (e.g. bio-ethanol, bio-diesel, and bio-dimethyl ether) and e-fuels produced from renewable energy, are excluded due to uncertainties regarding their future availability and cost-competitiveness[7,76].

$$C = \Sigma\Sigma\, \mathrm{vkt} * S * \mathrm{FCR} * F \qquad (1)$$

C denotes total CO_2 emissions of the road freight sector; vkt is total vehicle-kilometers-travelled per vehicle; S represents the vehicle stock; FCR is the average fuel consumption rate; and F refers to the fuel carbon intensity.

While previous models in integrated assessment modeling framework often overlook key operational efficiency metrics, we enhance the existing modeling approach to explicitly incorporate critical operational factors—such as vehicle empty running, load factor, VKT, and payload capacity. The vehicle stock for each type is determined not only by its role in the domestic road freight system (i.e., vehicle structure), but also by utilization at the vehicle level, which is influenced by these operational factors as shown in Equation (2). This approach aligns with findings from existing literature, which suggest that improvement in operational efficiency can lead to reductions in fleet size[23,30].

$$S = \frac{\mathrm{TKM}}{\mathrm{vkt} * (1 - \mathrm{Emp}) * \mathrm{LF} * \mathrm{Cap}} \qquad (2).$$

Here, TKM refers to the total tonne-kilometers traveled by a specific vehicle and powertrain type; *LF* denotes the average load factor or payload capacity utilization; Cap represents the average payload capacity per vehicle. vkt is the total vehicle kilometers traveled; Emp is the percentage of empty mileages; and vkt*(1-Emp) indicates laden, or revenue-generating, distance.

The model spans annually from 2020 to 2060. For base year (2020) calibration, total TKM and vehicle stock for the HDV sector are sourced from National Bureau of Statistics[71]. Fuel consumption rates are from CATARC (2021)[57]. Payload capacity for ICE-diesel, HEV-diesel and NGV vehicles are drawn from 2010 China Expressway Statistics[63] and ICCT (2017)[77]. For EV and FCV, payload capacity is from Feng (2022)[66], which reports that ZEVs have approximately 15% and 10% lower payload capacity for HFT and MFT, respectively, compared to diesel and NG vehicles.

Values for empty running ratio, load factor and VKT are derived on existing literature[3,57,63] and authors' calibration. VKT data specific to EVs and FCVs are based on Wang and Liang (2023)[65], which indicate ZEVs operate with roughly 25% lower VKT than other powertrain types. Fuel carbon intensity data are obtained from IPCC's *Guidelines for National Greenhouse Gas Inventories*[78].

The estimation of future TKM values follows the methodology outlined in Pan et al. (2018)[79]. Future energy consumption rates are assumed to improve in line with projections from Lu et al. (2023)[80] and SAE-China (2020)[81]. The future stock of each powertrain type is calculated using total vehicle stock derived from Equation (2), vehicle survival curves, and government targets for vehicle sales and phase-out by powertrain type. A uniform vehicle survival pattern is assumed across all powertrain types, based on data from Lu et al. (2023)[80] and Liu et al. (2020)[82]. Sales and retirement targets vary by powertrain type depending on the technological scenario, and are described in detail in the scenario settings section.

Projections for vehicle empty running, load factor and VKT are determined by assumptions regarding the market penetration of truck-hailing services and their effects on operational efficiency—these are also detailed in the scenario section. The payload capacity of ICE-diesel, hybrid diesel and natural gas vehicles are assumed to stay constant for both MFTs and HFTs. For zero-emission vehicles (ZEVs), including battery electric vehicles (EVs) and fuel cell vehicles (FCVs), performance gaps relative to other powertrain types (ICE-diesel, HEV-diesel and NGV) are assumed to gradually narrow, with payload disadvantages halved and VKT parity achieved by 2060 (Supplementary Fig. 4).

Decomposition of emission reduction by main contributing factors. Following Equation (1) and (2), the carbon emissions from road freight transport for vehicle type *i* and powertrain type *j* can be attributed to several driving forces. These include operational factors (empty running, load factor, payload capacity, VKT), technological factors (fuel efficiency and low-carbon technologies), and other factors (freight transport demand, fuel carbon intensity, and overall vehicle structure):

$$C_{ij} = \frac{C_{ij}}{E_{ij}} * \frac{E_{ij}}{\mathrm{TVKT_{ij}}} * \frac{\mathrm{TVKT_{ij}}}{\mathrm{TVKT\_Revenue_{ij}}} * \frac{\mathrm{TVKT\_Revenue_{ij}}}{\mathrm{ATKM_{ij}}} * \frac{\mathrm{ATKM_{ij}}}{\mathrm{TKM_{ij}}} * \frac{\mathrm{TKM_{ij}}}{\mathrm{TKM_{i}}} * \frac{\mathrm{TKM_{i}}}{\mathrm{TKM}} * \mathrm{TKM} \qquad (3),$$

where TVKT refers to total vehicle-kilometers-traveled, calculated as the product of VKT and vehicle stock; TVKT_Revenue represents the revenue-generating portion of TVKT; and ATKM denotes available capacity-kilometers[54,83].

C/*E* captures the fuel carbon intensity, and *E*/TVKT reflects fuel consumption rate. The ratio TVKT/TVKT_*Revenue* is the inverse of the revenue mileages share (i.e., one minus the share of empty mileage), and TVKT_Revenue/ATKM represents the inverse of the average vehicle payload capacity. The ratio ATKM/TKM is the inverse of load factor. $\mathrm{TKM_{i,j}}/\mathrm{TKM_i}$ and $\mathrm{TKM_i}/\mathrm{TKM}$ describe the distribution of freight activity across powertrain types (fuel structure) and vehicle types (vehicle structure), respectively.

The contribution of each factor to changes in carbon emission over selected years is estimated using the LMDI approach[84-85]:

$$\Delta C = \sum_n \Delta K_n \qquad (4),$$

$$\Delta K_n = \begin{cases} \sum_i \sum_j \frac{C_{ij}^t - C_{ij}^0}{\ln C_{ij}^t - \ln C_{ij}^0} * \ln \frac{K_n^t}{K_n^0} & if\ K_n^t \neq K_n^0 \\ 0 & if\ K_n^t = K_n^0 \end{cases} \qquad (5),$$

where K_n denotes the eight contributing factors in equation (3), and ΔC and ΔK_n represent the changes in carbon emissions and each contributing factor, respectively, between year *0* and year *t*.

Scenario settings. To evaluate the potential contributions of logistics and technology to decarbonizing China's MHDT road freight sector, we develop cross-cutting scenarios that integrate both pathways.

On the logistics side, we construct five scenarios representing possible future developments in truck-hailing services. Each scenario is associated with corresponding changes in vehicle operational efficiency—specifically, improvements in empty running, load factor, and VKT. The first scenario represents a business-as-usual (BaU) case, assuming that truck-hailing penetration remains at its current level.

In the second and third scenarios, we adopt more "optimistic" assumptions about the future development of truck-hailing in China, modeling its growth as linear and S-shaped trajectories, beginning in 2013. We take a market penetration rate of 22% in 2020, based on the proportion of truck drivers who rely exclusively on digital freight platforms, as reported in a recent truck driver employment survey[51]. We assume that truck-hailing services will eventually reach a saturation point at 80% market penetration. In addition to digital freight matching, contract logistics has played an important—albeit more traditional—role in China's road freight sector, typically involving large commercial fleets and long-term contracts[86-87]. Due to a lack of comprehensive statistics, we estimate the current market share of contract logistics at 11.4%, corresponding to the share of drivers who report stable sources of freight according to the same survey[51]. We further assume that contract logistics began developing in 2001, when China entered the World Trade Organization, and has since grown linearly toward a saturation level of 20%.

The fourth and fifth scenarios represent "medium" projections, assuming continued growth in freight digitalization—following linear and S-shaped trajectories, respectively—but at roughly half the rate of the "optimistic" scenarios. Similarly, the market adoption rate of contract logistics is also assumed to halve in these cases. Supplementary Fig. 5a presents the projected market penetration rates of truck-hailing services and contract logistics across all five scenarios. In the optimistic projections, truck-hailing services are expected to reach market saturation by 2039 under the linear growth model and by 2036 under the S-shaped growth model, while contract logistics reaches saturation by 2038. In the medium projections, truck-hailing services reach market saturation by 2057 and 2052 under the linear and S-shaped growth models, respectively, while contract logistics is projected to plateau at 20% market penetration by 2056.

We assume that all vehicles with access to truck-hailing services in the future will achieve operational performance levels—specifically in terms of empty running, load factor and VKT—comparable to those observed in the national truck-hailing sample. Since our analysis indicates that owner-operators in the sample exhibit similar performance in empty mileages, VKT and load factor to that of large commercial fleets or contract logistics, we make a further simplifying assumption: vehicles engaged in contract logistics will perform similarly to truck-hailing users. As a result, average market operational efficiencies can be estimated as the weighted averages of performance metrics from two groups—vehicles using truck-hailing services or contract logistics, and the remaining owner-operators who rely on neither. In essence, average market operational efficiency is primarily driven by the combined market shares of truck-hailing and contract logistics (Supplementary Fig. 5b).

We define two scenarios along the technological dimension. The current policy scenario (CPS) reflects a trajectory shaped by existing and announced low-carbon technology focused policies for near-term targets. These include China's National Determined Contributions (NDCs), the *New Energy Vehicle Industry Development Plan for 2021–2035*[88], the *Action Plan for Carbon Dioxide Peaking Before 2030*[89], and the *Energy Conservation and New Energy Vehicle Technology Roadmap 2.0*[81]. While these policies emphasize near-term progress through 2035, they fall short of supporting deep decarbonization beyond that timeframe. In contrast, the carbon neutrality scenario (CNS) outlines a more ambitious pathway aligned with China's long-term goal of achieving carbon neutrality by 2060. This scenario assumes accelerated deployment of zero emission vehicles, including battery electric and hydrogen fuel cell trucks, along with more aggressive sales targets for ZEVs and earlier market phase-out deadlines for ICE and hybrid vehicles. These assumptions draw on projections from Feng (2022)[66], iCET (2021)[90], and SAE-China (2023)[91]. In essence, the key difference between the CPS and CNS scenarios lies in the pace of low-carbon technology adoption, which in turn drives divergence in vehicle powertrain composition.

Supplementary Fig. 6 presents the market share of all vehicle and powertrain types at five-year intervals under two technological scenarios, while Supplementary Fig. 7 illustrates vehicle operational efficiency metrics across the combined logistics and technological scenarios.

Data Availability

The raw truck-hailing data are protected and are not available due to commercial confidentiality. Other data that support the findings of this work are listed in the Methods section. Aggregated data used to generate the figures are available at https://zenodo.org/records/18439095.

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Acknowledgement

This research was supported by the National Key Research and Development Program of China (2024YFE0115800), the National Natural Science Foundation of China (No. 52232011), the introduced innovative R&D team of Guangdong under Grant 2023ZT10L145, and the Sichuan Science and Technology Program “PIANJI” Project (No. 2025HJPJ0011). We also gratefully acknowledge support from KAPSARC, the Tsinghua University-Toyota Research Center, and the Carbon Neutrality and Energy System (CNEST) program initiated by Tsinghua University.

Author Contributions

X.X., T.P. and X.O designed the research. X.X., T.P., Z.X., M.G., D.L. and X.L. acquired and prepared the data. X.X., T.P. and Z.X. performed the analysis. X.X. and T.P. wrote the paper. S.O. and Z.L. supervised the research, and reviewed and revised the paper.

Competing interests

The authors declare no competing interests.

Tables

Table 1 Comparison of percentages of empty running across vehicle types and duty cycles.

Data	Vehicle type	Intra-province	inter-province	total
Truck-hailing Sample	MFT	14%	10%	10%
	HFT	14%	10%	10%
Tolled Expressway (2014)	MFT	31%	23%	28%
	HFT	29%	11%	18%

Table 2 Comparison of load factor (capacity utilization) across vehicle types.

Vehicle type	Truck-hailing Sample	Tolled Expressway 2010
MFT	87%	73%
HFT	88%	87%

Note: Only weight is used to calculate vehicle load factor. Volume is not accounted for when considering load-vehicle matching.

Table 3 Comparison of daily VKT across vehicle types.

	Truck-hailing Sample	MOT Pilot Project w/ Truck-hailing[55]	MOT Pilot Project w/o Truck-hailing[55]	MOT Road Freight Survey 2019[56]	CATARC Survey 2021[57]	ANL China Fleet Model 2018[58]	IEA Truck Report 2017[1]
MFT	474	400	267	190	88	110	68
HFT	474	400	267	190	133	110	99

Note: Annual mileages are reported in CATARC (2021), Argonne (2018) and IEA (2017) and are converted to daily values for comparison.

Figures

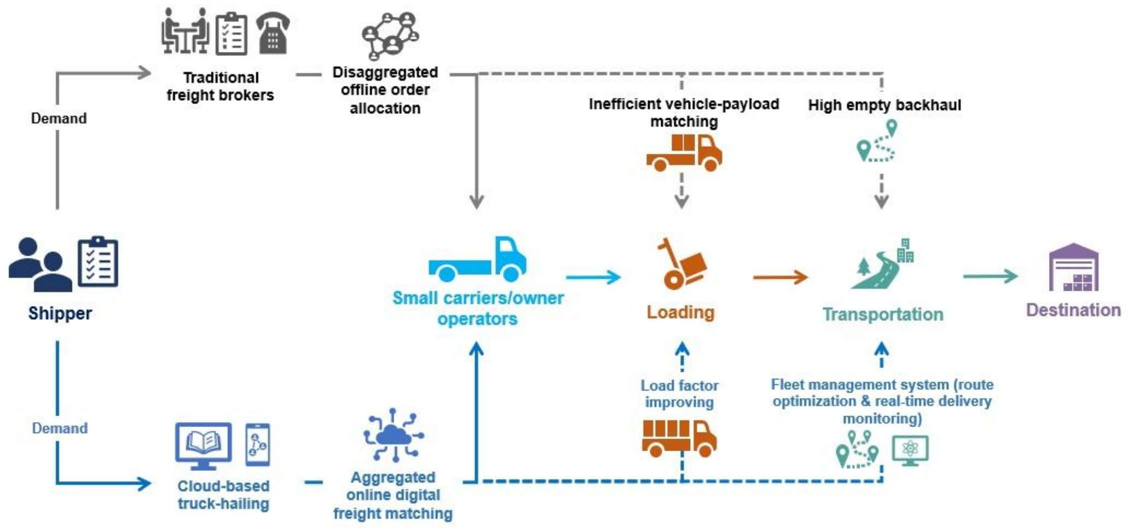


Fig. 1 | A comparison of the logistics impacts of two business models. Cloud-based truck-hailing services are found to have higher operational efficiency than conventional offline vehicle-payload matching practices in China.

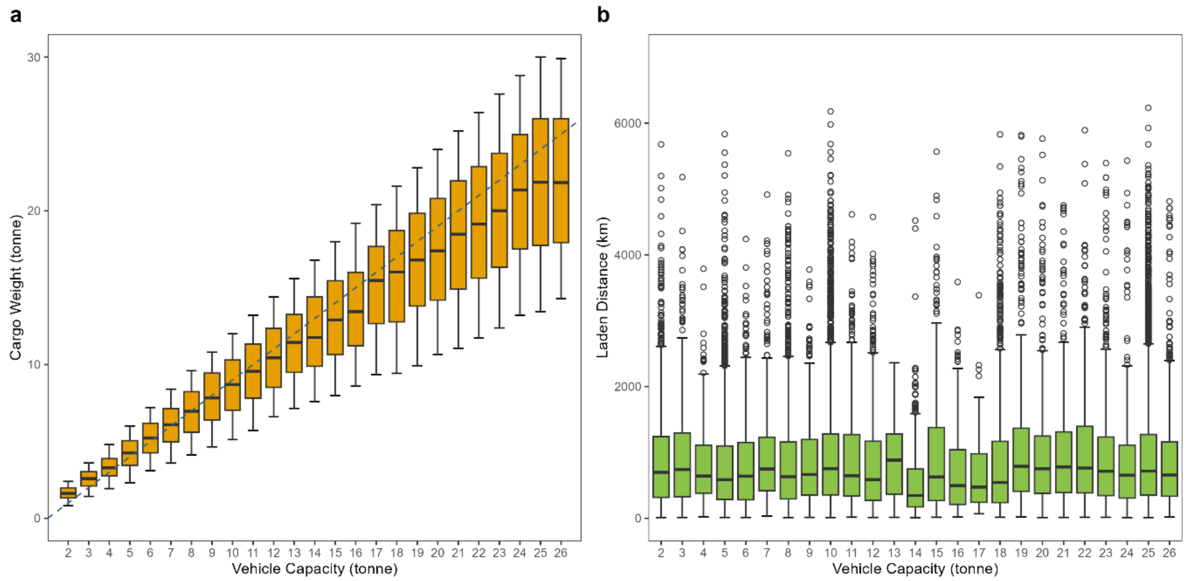
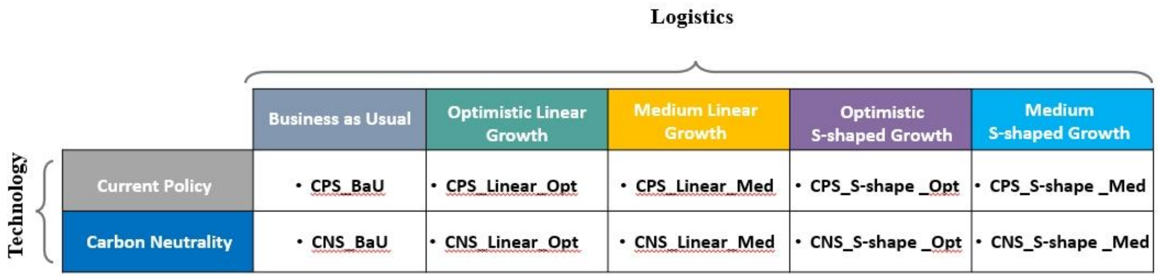


Fig. 2 | Load-vehicle and journey-vehicle matching patterns in the national truck-hailing sample. a, distribution of cargo weight against vehicle capacity. b, distribution of origin-destination laden distance against vehicle capacity. Distribution of empty running distances are not reported in b. Vehicle capacity is divided into bins based on tonnage values. A 45-degree dashed line is fitted in a to indicate 100% load-vehicle matching. Boxplots display the median (center line) and interquartile range (box). Whiskers represent 1.5 times the interquartile range, and observations falling beyond this threshold are plotted as individual outliers.



	Business as Usual	Optimistic Linear Growth	Medium Linear Growth	Optimistic S-shaped Growth	Medium S-shaped Growth
Current Policy	• CPS_BaU	• CPS_Linear_Opt	• CPS_Linear_Med	• CPS_S-shape _Opt	• CPS_S-shape _Med
Carbon Neutrality	• CNS_BaU	• CNS_Linear_Opt	• CNS_Linear_Med	• CNS_S-shape _Opt	• CNS_S-shape _Med

Fig. 3 | China's potential medium- and heavy-duty road freight transport decarbonization pathways. CPS_BaU: current policy scenario with truck-hailing penetration remaining constant at the current level. CPS_Linear_Opt: current policy scenario with optimistic linear growth of truck-hailing services. CPS_S-shape_Opt: current policy scenario with optimistic S-shaped growth of truck-hailing services. CPS_Linear_Med: current policy scenario with medium linear growth of truck-hailing services. CPS_S-shape_Med: current policy scenario with medium S-shaped growth of truck-hailing services. CNS_BaU: carbon neutrality scenario with truck-hailing penetration remaining constant at the current level. CNS_Linear_Opt: carbon neutrality scenario with optimistic linear growth of truck-hailing services. CNS_S-shape_Opt: carbon neutrality scenario with optimistic S-shaped growth of truck-hailing services. CNS_Linear_Med: carbon neutrality scenario with medium linear growth of truck-hailing services. CNS_S-shape_Med: carbon neutrality scenario with medium S-shaped growth of truck-hailing services.

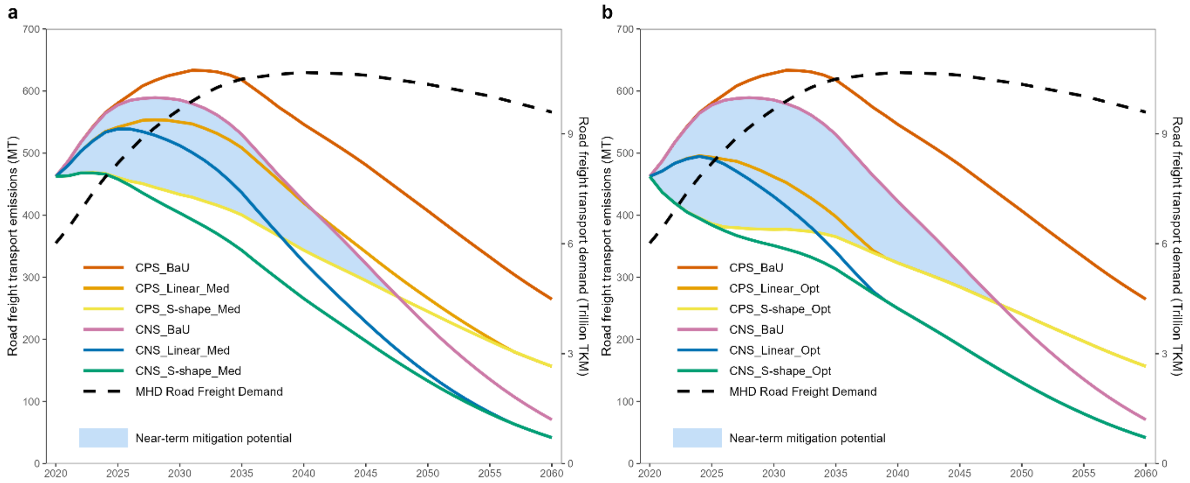


Fig. 4 | China's potential medium- and heavy-duty road freight transport decarbonization pathways under all scenarios. Projected total road freight transport demand is shown in dashed line (right axis). a, projected CO2 emissions under BaU and medium (Med) scenarios. b, projected CO2 emissions under BaU and optimistic (Opt) scenarios. The shadings reflect the near-term mitigation potential of logistics improvements relative to rapid low-carbon technology adoption.

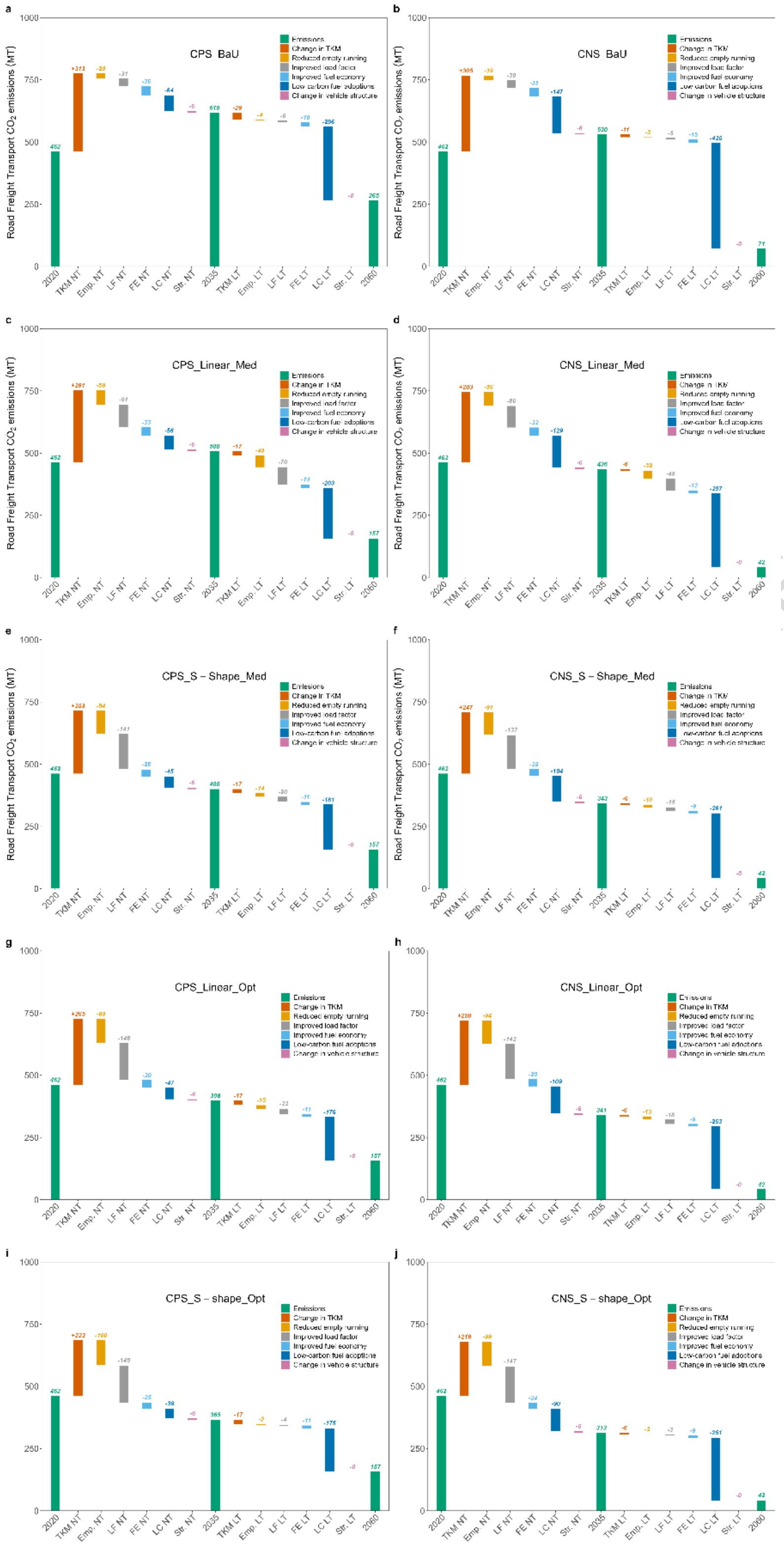


Fig. 5 | Emission reduction contributions by logistics and technological factors for all scenarios, analyzed using the LMDI approach. **a,** Emission reduction contributions under CPS_BaU scenario. **b,** Emission reduction contributions under CNS_BaU scenario. **c,** Emission reduction contributions under CPS_Linear_Med scenario. **d,** Emission reduction contributions under CNS_Linear Med scenario. **e,** Emission reduction contributions under CPS_S-shape_Med scenario. **f,** Emission reduction contributions under CNS_S-shape_Med scenario. **g,** Emission reduction contributions under CPS_Linear_Opt scenario. **h,** Emission reduction contributions under CNS_Linear_Opt scenario. **i,** Emission reduction contributions under CPS_S-shape_Opt scenario. **j,** Emission reduction contributions under CNS_S-shape_Opt scenario. Year-over-year comparisons are made, specifically between 2020 and 2035, and between 2035 and 2060. The effect of vehicle payload capacity change is omitted from the figures, as it registers zero in both near-term and long-term analyses. The bars depict emission variations resulting from changes in demand (TKM), empty running (Emp.), load factor (LF), fuel economy (FE), low-carbon fuel adoptions (LC), and vehicle structure (Str.) in both near-term (NT) and long-term (LT).

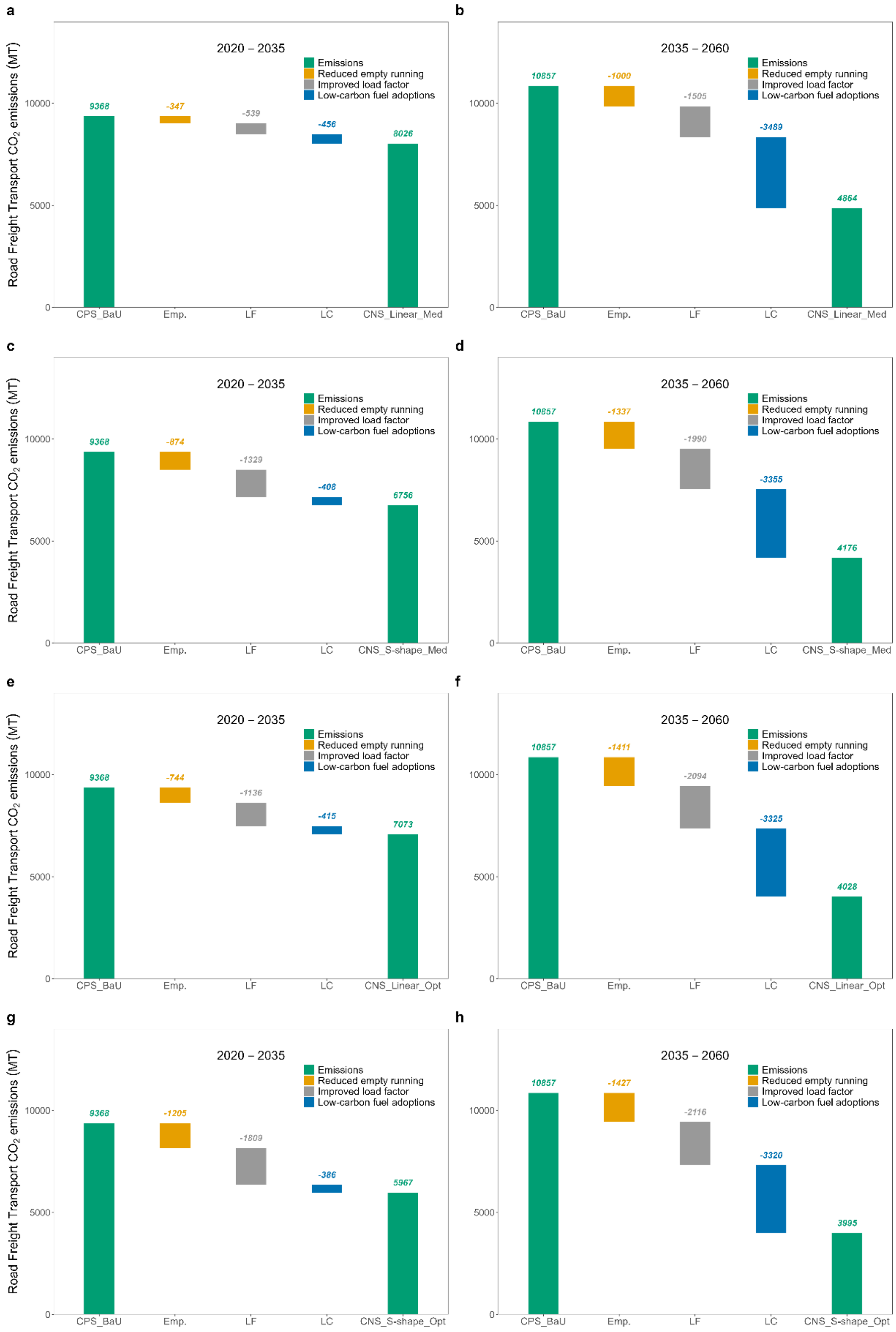


Fig. 6 | Cumulative emission reduction contributions by logistics and technological factors when compared against the baseline CPS_BaU scenario, analyzed using the LMDI approach. a and b compare the CNS_Linear_Med scenario against the baseline. c and d compare the CNS_S-shape_Med scenario against the baseline. e and f compare the CNS_Linear_Opt scenario against the baseline. g and h compare the CNS_ S-shape_Opt scenario against the baseline.

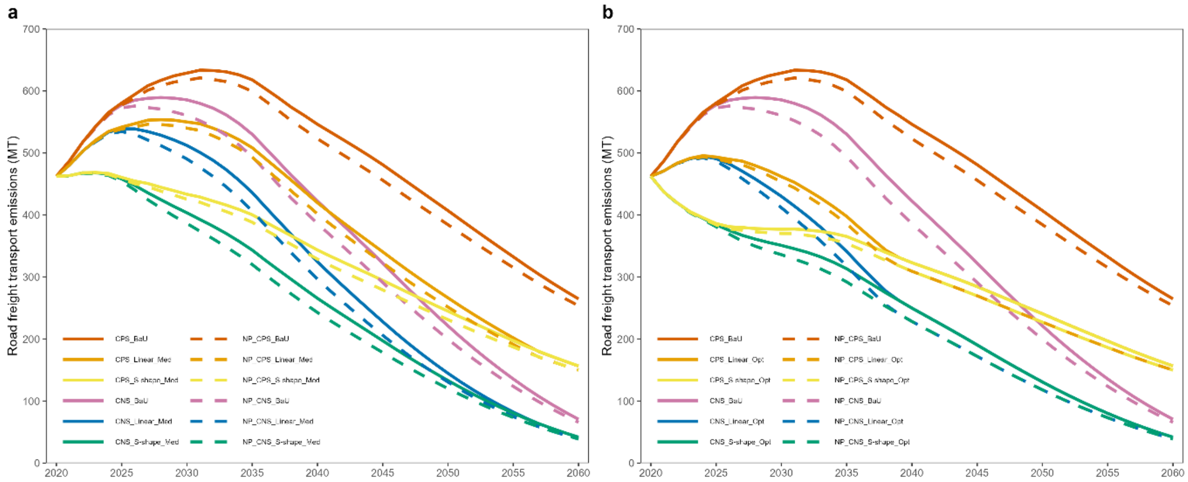


Fig. 7 | A comparison of total emissions against counterfactual scenarios where ZEVs are assumed to have no operational performance penalties (range and capacity). NP_CPS_BaU, NP_CPS_Linear, NP_CPS_S-shape, NP_CNS_BaU, NP_CNS_Linear, and NP_CNS_S-shape are counterfactual scenarios of CPS_BaU, CPS_Linear, CPS_S-shape, CNS_BaU, CNS_Linear, and CNS_S-shape, respectively in the main analysis, assuming no penalty (NP) in ZEV's operational performance. a, projected CO2 emissions under BaU and medium (Med) scenarios. b, projected CO2 emissions under BaU and optimistic (Opt) scenarios.

Editor Summary

This study quantifies the emission impacts of operational efficiency improvements and constraints in China's fast-evolving road freight sector, finding logistics enhancement a viable strategy for the sector's decarbonization.

Peer review information: *Nature Communications* thanks the anonymous reviewers for their contribution to the peer review of this work. A peer review file is available.