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Sustainable Infrastructure Programme in Asia

Evaluating the relationships between connectivity, decarbonisation and resilience in freight transport

Applications to Central and Southeast Asia

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The Sustainable Infrastructure Programme in Asia

This paper is part of the Sustainable Infrastructure Programme in Asia (SIPA), funded by the German International Climate Initiative (IKI) and led by the OECD. SIPA aims to support countries in Central and Southeast Asia in their transition towards energy, transport and industry systems aligned with the Paris Agreement and Sustainable Development Goals.

The ITF leads the transport component of the SIPA programme (SIPA-T). The SIPA-T project helps decision makers in Central and Southeast Asia by identifying policy pathways for enhancing the efficiency and sustainability of regional transport networks. Project outputs include two regional studies that explore opportunities to improve the connectivity, sustainability, and resilience of freight transport systems in Central and Southeast Asia.

This paper is the fourth in a series of four ITF expert working papers that collectively provide the methodological foundation for the two SIPA-T regional freight transport studies. The full series includes the following papers:

1. *Enhancing freight transport connectivity through analytical frameworks* (Ruth Banomyong)
2. *Enhancing freight transport decarbonisation through analytical frameworks* (Alan McKinnon)
3. *Enhancing freight transport resilience through analytical frameworks* (Jasper Verschuur)
4. *Evaluating the relationships between connectivity, decarbonisation and resilience in freight transport* (Alan McKinnon)

Access these papers, more information, and other SIPA-T project deliverables at the link below:

https://www.itf-oecd.org/sustainable-infrastructure-programme-asia-transport

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Introduction

The first three papers in this series discuss connectivity, decarbonisation, and resilience separately. This summary paper examines the inter-relationships between them, assessing the extent to which they are mutually reinforcing or counteracting, and proposes quantitative metrics to measure and evaluate them. It does this within an assessment framework that maps interconnections between the connectivity, decarbonisation and resilience of freight transport systems.

Much of the literature on the development of transport systems in Asian countries suggests that there is a close alignment of connectivity, sustainability and resilience goals. For example, frequent references are made to the concept of sustainable connectivity in reports by ESCAP (2019) and the ITF (2019a). Connectivity has also been described as a "catalyser for sustainable development" in Asia, helping countries achieve the broad set of UN Sustainable Development Goals (SDGs), several of which are dependent on efficient and reliable freight movement (ESCAP, 2023). The upgrading of transport infrastructure in Central Asia is advocated as a means of diversifying "trade links to make Eurasian supply chains resilient" (ITF, 2022), while the World Bank Group (2022) outlines a series of transport infrastructure projects in Southeast Asia that are promoting "green, resilient and inclusive development".

Formally defining and operationalising the relationships between connectivity, decarbonisation and resilience in terms that would permit analysis and evaluation is, nevertheless, difficult. This is the case for most regions, but particularly so in Central and Southeast Asia, for three reasons. First, they are at a stage in their economic development when the connectivity of transport networks is rapidly increasing. Second, their share of global freight transport emissions is forecast to rise steeply over the next few decades (ITF, 2023). Third, Southeast Asia is predicted to suffer above-average exposure to future climate risk (Eckstein et al., 2021), while Central Asia is particularly susceptible to geopolitical risk.

As discussed in the previous papers in this series, different definitions of the terms connectivity, sustainability and resilience are used in the academic and governmental literature. This makes it difficult to generalise the relationship between the three concepts. In this report, the definition of sustainability has been simplified by focusing on a single negative externality, greenhouse gas (GHG) emissions, and one process, decarbonisation. The terms connectivity and resilience have remained more broadly defined:

- Connectivity as "the efficiency and effectiveness of infrastructure and services that facilitate the movement of goods across various transport modes within and between countries, encompassing physical infrastructure, policies, institutional frameworks, logistics services and freight owners' requirements" (Banomyong, 2024).
- Resilience as "the ability to cope with, recover from, and adapt to external shocks to the freight transport network" (Verschuur, 2024).

In freight transport policy-making and planning, the three concepts are usually analysed separately, and goals are assigned that are mutually exclusive. Connectivity is seen primarily as having economic significance, decarbonisation as an environmental imperative and resilience as a strategic concern with economic, social and security impacts. As a consequence, the interdependencies between them are often overlooked. Transport policy-making can then become "siloed", and policy initiatives misaligned. By making the connections between connectivity, decarbonisation and resilience more explicit, this integrative paper may help policy-makers and planners to exploit potential synergies and manage trade-offs more effectively. It can also promote the adoption of a more holistic approach to the development, implementation and evaluation of freight transport policy.

Before examining the relationships between connectivity, decarbonisation, and resilience, it is important to clarify the vocabulary, the scoping of the exercise and the choice of metrics. They are reviewed in the next section.

Terminology and scoping

In the transport policy literature, many English words with similar meanings are used interchangeably, sometimes in ways that may confuse the reader. The lexicon contains terms such as attribute, criterion, dimension, element, entity, index, indicator, lever, metric and parameter. This paper adopts three of these words as being central to the discussion:

- Entity: the generic term for the phenomena that are being investigated, in this case, connectivity, decarbonisation or resilience. Decarbonisation differs from the other two in being a process rather than a phenomenon that can be assessed at a particular point in time. To maintain consistency, this entity will be defined as the extent of decarbonisation, in other words, the level of carbon emissions from a freight transport system.
- Attribute: one of the fundamental features of the entity being examined. An important distinction can be drawn between physical attributes and attributes that are influenced by managerial decision-making. All of the connectivity attributes identified for the analysis fall into the first category. In response to physical changes in connectivity, companies modify their operations, restructure their logistical systems and reconfigure their supply chains in ways that affect their carbon intensity, their vulnerability and the rate at which they recover from disruptions. A distinction can, therefore, be drawn between the direct effects of connectivity on transport emissions and resilience and the indirect effects mediated by what might be called macro-logistic adjustments. This pushes the boundary of the analysis beyond the transport system into the management of logistics and supply chains. This is reflected in the range of attributes proposed below for decarbonisation and resilience.
- Metric: a quantitative measure of changes in an attribute. The choice and definition of a metric are constrained by the availability of data, particularly in lower-income countries where public data collection systems are often less well-developed.

Connectivity attributes

Eight network-specific attributes have been identified for connectivity relating both to transport infrastructure and the freight services that use it.

1. Extent: size of the geographical area served by the transport network.
2. Density: ratio of route-kilometres to the area served; the directness of interconnections between any two points in the network.
3. Multimodality: proportions of total network-kilometres and freight carrying capacity dedicated to particular transport modes and the density of interchange points at which freight can transfer between modes.
4. Maximum capacity: quantity of freight traffic that can be carried in a given time period.
5. Configuration: structure of the network in terms of the orientation of routes, distribution of carrying capacity (e.g. “mesh”, corridor, hub-and-spoke) and segregation of traffic types.
6. Dimensions: ability of a network to accommodate freight vehicles of particular sizes, weights, manoeuvrability and energy requirements.

7. Alignment: extent to which the structure of the network matches the spatial distribution of economic activity.
8. Condition: quality of the infrastructure, reflected in maintenance standards, safety record, ability to withstand climatic and geophysical stresses, etc.

The definition of connectivity can be expanded to supplement transport infrastructure with energy and communication infrastructures. A strong case can be made for adopting this multi-infrastructure approach as the decarbonisation of freight transport entails its electrification and as digitalisation can significantly enhance both its sustainability and resilience. The risk of disruption can also propagate rapidly across transport, energy and IT infrastructures, creating the need for resilience strategies that embrace all three. In the present context, however, connectivity is defined solely in transport terms, and the list of metrics is compiled accordingly.

Decarbonisation attributes

The choice of five attributes for decarbonisation is derived from the so-called “five-lever framework” for freight transport decarbonisation, discussed in the decarbonisation paper of this series (McKinnon, 2024a). Like the Kaya Identity, which has underpinned much macro-level analysis of carbon mitigation (Kaya, 1990), this framing of freight decarbonisation is based on a series of ratios. They link GDP, which is determined exogenously, to the level of carbon emissions from freight transport:

1. Freight transport demand: ratio of tonne-kilometres to GDP. The freight transport intensity of an economy varies with the level of development and can be influenced by public policy.
2. Modal split: ratio of tonne-kilometres moved by lower carbon transport modes to total tonne-kilometres.
3. Vehicle utilisation: ratio of tonne-kilometres to vehicle-kilometres, which is a measure of the average load factor (here, the term vehicle is applied cross-modally to trucks, rail wagons, trains, ships, and barges).
4. Energy efficiency: ratio of vehicle-kilometres to the energy consumed in moving the vehicles.
5. Carbon intensity: ratio of carbon emissions to energy consumed. This is an energy-based definition of carbon intensity.

All of the managerial and public policy levers that can be used to cut freight emissions relate to one or more of these five attributes.

This framework relates to the decarbonisation of freight movement and, to date, has made little reference to the development and maintenance of the transport infrastructure that carries the freight traffic. The adoption of a life-cycle approach to freight decarbonisation, as discussed in McKinnon (2024a), permits the inclusion of infrastructure-related emissions and a more holistic, long-term assessment of the carbon impact of a freight transport system.

Resilience attributes

Six attributes are identified for resilience at the transport, logistics and supply chain levels.

1. Sourcing: average distance that freight consignments move on a trip or supply chain basis. The extent of the area from which goods are procured.
2. Intermodality: extent to which the use of different transport modes spreads the risk of disruption and the ease with which freight consignments can be switched between modes at short notice when a disruption occurs.
3. Redundancy: amount of spare capacity and inventory in logistical systems that can act as buffers against interruptions to the flow of goods.
4. Scheduling: degree to which production and logistics processes are synchronised, for example, by just-in-time (JIT) replenishment, and hence susceptible to delay.
5. Diversity: range of options available for the routing of freight, the multiple sourcing of supplies, the ability to switch between energy sources, etc.
6. Visibility: nature and speed of communication about disruptions to providers and users of freight transport services and other stakeholders.

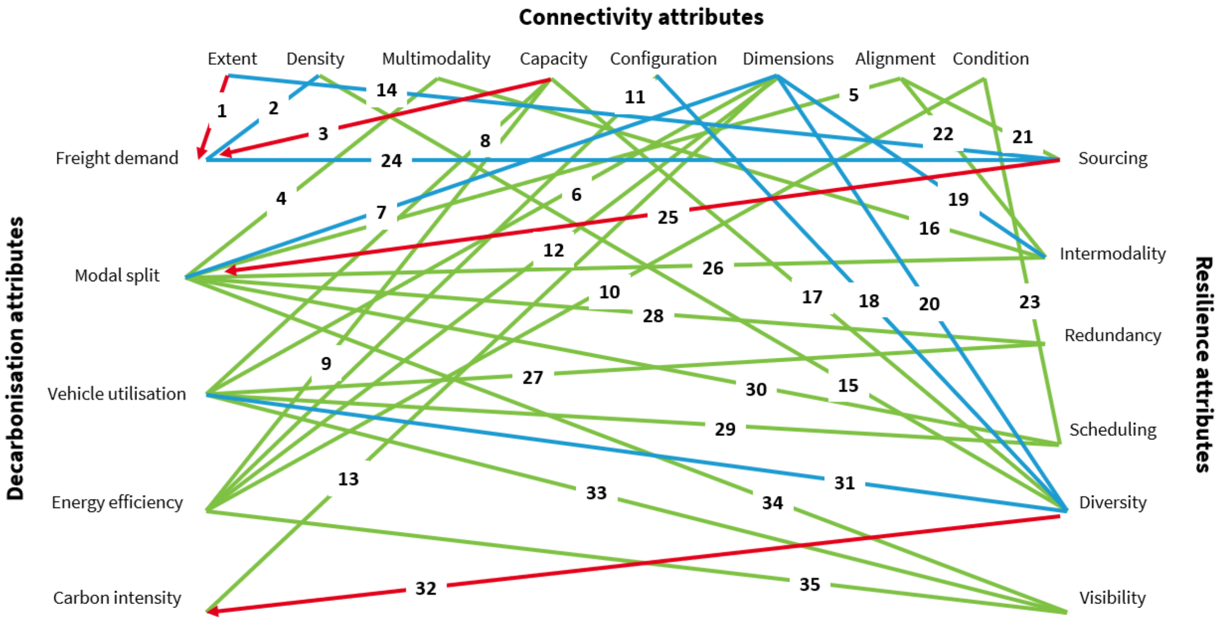
The US National Climate Assessment (National Academies, 2016) distinguished initiatives that minimise the degree of disruption within the transport sector from those that minimise the external consequences of those disruptions, which cannot be suppressed internally. This two-stage decoupling of a disruptive event from its potential economic and social impacts requires action by both the operator of the transport system and the user of the freight transport service. It incorporates the management of logistics systems and supply chains into the resilience-building process, as reflected in the list of attributes.

Mapping the relationships between connectivity, decarbonisation and resilience

Among numerous possible interconnections between the sets of connectivity, decarbonisation and resilience attributes listed above, 35 exhibit a significant degree of interdependence. They are plotted in Figure 1, illustrating the degree and complexity of interdependence between the three entities. On the assumption that all the connectivity attributes increase, the green lines represent mutually reinforcing relationships (or synergies), the red lines signify a conflict (or trade-off), and the blue lines are a hybrid situation where, depending on the circumstances, the relationship can be either supportive or inhibiting. Two-thirds of the relationships fall into the first category, while a quarter are classified as hybrid. Those conflicting relationships involving a trade-off relate to the growth in freight demand, modal shift and the transition to renewal energy. Where a conflict exists between attributes, the typical direction of the negative impact is indicated by arrows in Figure 1. The relationships are also summarised in tabular form in Annex A.

The following sections explore, on a pair-wise basis, the underlying complexities and nuances in the 35 relationships between the different sets of attributes, the code numbers in square brackets corresponding to the links in Figure 1.

Figure 1. Map of interactions between freight transport connectivity, decarbonisation and resilience



Relationship between connectivity and decarbonisation

This subsection will explore the effects of improved connectivity on each of the decarbonisation attributes.

1. Transport demand.

Increases in the extent, density and capacity of transport infrastructure generally promote the growth of freight movement [1, 2 and 3]. By reducing freight transit times and costs, they encourage companies to geographically extend the distribution of their products and sourcing of their supplies and to serve wider areas from more centralised facilities. As discussed in the decarbonisation paper of this series (McKinnon, 2024a), these spatial processes are primary drivers of freight traffic growth, intrinsic to economic development and currently very active in the emerging economies of Asia.

Increased network density can permit more direct routing of freight flows across a country or region [2]. In theory, the greater the density, the shorter will be the average distance between any pair of origins and destinations. This does not necessarily translate into a shorter average length of haul for freight traffic, however, as the routing of that traffic will be sensitive to other connectivity attributes, particularly configuration, alignment and capacity. Link [2] is therefore classified as hybrid.

In purely transport terms, extending the reach of a network [1] is likely to increase traffic volumes and related emissions. Hence the designation of this link as a trade-off. If, however, the carbon analysis were broadened beyond freight transport and logistics to measure the full life cycle of the transported product, the outcome might be different. Increases in carbon emissions from freight transport could be exceeded by carbon savings from the sourcing of materials from lower-carbon locations and suppliers that are only made accessible by improved connectivity. Applying this approach to international trade has revealed that around a third of trade (by value) yields a carbon saving when the carbon intensity of production in the exporting country is lower than that in the importing country (Cristea et al., 2013). It is not known what the comparable proportion is for Central and Southeast Asia, though it is likely to be significant and, as Paz (2023) explains, it can also be augmented by, inter alia, “facilitating trade in environmental goods and services, diversifying exports away from primary products into higher-value products, and leveraging free trade agreements to promote climate action”. Improved connectivity can be added to this list.

There is also an important modal dimension to connectivity. If connectivity is increased primarily by extending and upgrading rail and waterway networks, the additional freight movement it generates will have a relatively low carbon intensity [4]. When official reports advocate “sustainable connectivity” improvements for Asian countries (e.g. ESCAP, 2019), they generally want investments in rail and waterborne infrastructure to be prioritised. This leads the discussion to the second decarbonisation attribute: modal split.

2. Modal split.

Increasing the extent, density, capacity and dimensions of the networks of low-carbon transport modes contributes to the overall multimodality of the freight transport system [4]. This applies mainly to rail networks, though it can also be relevant to countries relying heavily on waterborne transport, as in Southeast Asia. Extending the geographical reach of these modes allows them to more fully exploit their comparative advantage in long-distance movement. This is likely to facilitate a shift to lower carbon modes.

The interconnection of modal networks can be improved through the creation of intermodal hubs. It is through the use of such terminals that companies whose premises cannot justify a direct connection to rail or waterway networks gain access to lower-carbon transport modes. Increasing the density of these modal interchange points reduces the length, duration and cost of road feeder movements, significantly improving the competitiveness of intermodal services, which are generally more carbon-efficient.

The "alignment" of low-carbon modes with the spatial distribution of economic activity [5] can be enhanced by physically connecting industrial and logistical premises generating large amounts of freight traffic to their networks. This applies where they are close enough to justify investment in a direct link, such as a rail siding or "spur". Such investment offers a much greater return when these premises are clustered in an industrial complex, distribution park, or "freight village" (Baydar et al., 2017). Concentrating freight-generating activity on one site offers many agglomeration benefits (Sheffi, 2012), of which easier and more economical access to alternative transport modes can be one of the most important. This usually requires land use planning policies that are conducive both to the clustering of industrial and logistical activity and the promotion of multimodal freight strategies. The challenge often lies in reconciling these goals with other land-use objectives unrelated to logistics (McKinnon, 2009).

3. Vehicle utilisation.

Raising the dimensions of a road network accommodates trucks of greater length, width, height, axle weight and gross weight [6]. The resulting increase in carrying capacity by mass and volume permits greater load consolidation. Where the extra capacity is well-utilised, the energy intensity and carbon intensity of the road freight operation can be reduced.

An important stage in the infrastructural upgrading process is when articulated tractor-trailer combinations can be accommodated with maximum lengths of 16-18 metres and maximum weights of 38-44 tonnes. The use of articulated vehicles can also increase average load factors by decoupling the loading/unloading of trailers from delivery schedules in so-called "drop-and-hook" operations.

A later stage in this process opens the road network to "high-capacity transport (HCT)", comprising the use of much longer trucks of 25-34 metres and gross weights of 50-70 tonnes. Experience of HCT in numerous countries has shown that high-capacity vehicles "can reduce carbon emission in the range of 15% to 40% depending on the vehicle configuration" (ITF, 2019). Significant net reductions in emissions can be achieved even after allowance for second-order effects, most notably a modal shift from rail to road. This "reverse" modal shift in environmental terms (D-fine, 2024) can be minimised by expanding the carrying capacity [8] and dimensions [7] of the rail track and rolling stock and ensuring that both are adequately used.

Allowance should also be made for two other potential second-order effects of relaxing vehicle and vessel size and weight limits. First, by making freight transport cheaper, the resulting scale economies can inflate demand for freight transport. An increase in tonne-kilometres can then erode some of the environmental benefits of consolidating the freight in fewer trips. This "induced traffic" argument is often advanced by those opposing increases in vehicle weights and dimensions, though there is little evidence to support it. A review of the arguments for and against high-capacity transport by the ITF (2019) acknowledged that it "will tend to result in additional freight demand" but concluded that "the effect is likely to offset only a small part of environmental gains". Second, the larger a vehicle or vessel is, the more constrained its accessibility is likely to be to lower-capacity routes and terminals, requiring it to follow more circuitous paths and to rely more heavily on less efficient, more carbon-intensive feeder services.

Vehicle load factors can also be raised by increasing infrastructural capacity, thereby relieving congestion [8]. This increases the reliability of delivery schedules and gives transport operators greater confidence to backload their vehicles and find load-sharing opportunities. These opportunities can also be more easily, quickly, and profitably found and exploited when the connectivity of communication networks is improved.

In a Digital Transformation Scenario spanning road, rail and maritime freight operations, Chen et al. (2022) found the potential for significant GHG savings resulting from increases in "average load utilisation".

4. Energy efficiency.

Improvements in various aspects of connectivity can reduce energy consumption per freight vehicle-kilometres on road and rail networks in several ways:

- Easing traffic congestion by expanding route capacity or improving network management allows freight traffic to move at more energy- and carbon-efficient speeds [9].
- Upgrading and maintaining road pavements and rail tracks to a higher standard generally enables trucks and trains to travel more energy-efficiently [10].
- The use of tunnelling and cuttings to minimise gradients on road and rail networks reduces the energy intensity of freight movement but greatly increases the embodied GHG emissions in the respective infrastructures (Pritchard and Preston, 2018) [10]. Vehicle-related energy and GHG savings must, therefore, be set against these higher infrastructural emissions in a Life Cycle Assessment, as discussed in the decarbonisation paper in this series (McKinnon, 2024a).
- The segregation of faster passenger trains from slower freight trains, a "configuration" variable, as happens where separate high-speed passenger networks are constructed, allows the latter to travel at more consistent speeds and avoids the loss of momentum when they need to be temporarily diverted into sidings or refuges to clear paths for express trains [11].
- The electrification of rail networks generally improves the energy efficiency of rail freight operations [12]. The energy efficiency of an electric locomotive is estimated to be around three times higher than that of a diesel one (RIA, 2023).

5. Carbon intensity.

Network electrification, which is subsumed within the "dimensions" aspect of connectivity, applies mainly to this decarbonisation attribute and is seen as a primary means of achieving carbon-neutral freight movement by rail and road in the longer term [13]. Only around a third of the rail network in the Asia Pacific region is electrified (ESCAP, 2021), with national proportions ranging from 0 to 90%. The potential exists, therefore, to substantially increase electrical connectivity across the Asian rail network.

Several European countries have been examining the costs and benefits of electrifying highway networks for the decarbonisation of trucks, two of which (Germany and Sweden) have been trialling this technology. As yet, there is no evidence of road electrification being explicitly considered as a policy option in Central and Southeast Asia. The magnitude of the carbon benefits of transport network electrification depends heavily on the carbon intensity of grid electricity, which also varies widely across the continent.

The provision of battery charging for road freight vehicles will become an increasingly important dimension of connectivity as it will extend the delivery range of the new generation of electric trucks. Whatever methods of freight transport electrification dominate in the two Asian regions, electricity grids will need to be substantially upgraded to provide the necessary power for low-carbon trucks and freight trains. The use of biofuels as transitional sources of lower-carbon energy over the next 10 to 20 years, mainly in the road freight sector, will also require the expansion of refuelling networks.

Relationship between connectivity and resilience

Increases in connectivity generally improve the resilience of transport and logistics systems, though when connectivity is “decomposed” into its various attributes, some potential conflicts with resilience-building strategies emerge. The implications for resilience will be examined for each of the connectivity attributes.

1. Extent.

Geographically expanding a transport network encourages companies to source and market their products over wider areas, increasing the average distance that vehicles and products travel. This lengthening of supply lines is often considered to increase the risk of disruption [14], or conversely, it has been observed that “supplier-customer proximity” reduces the perception of risk (Huang and Fan, 2023). In practice, however, supply chain risk is more closely associated with location- and supplier-specific factors than distance per se (McKinnon, 2024b). Furthermore, any distance-related risk is likely to be mitigated in the case of new infrastructural investment by the high standard to which new roads and rail lines are typically constructed.

2. Density.

As density increases, the number of alternative routes between any two points in the network multiplies, spreading the risk of a particular freight consignment not being able to reach its destination on time. Density and the diversity attribute of resilience are, therefore, likely to be closely correlated, in particular on a larger network level [15].

3. Multimodality.

Where a freight transport system comprises different modal networks (e.g. road, rail and inland waterway) interconnected by numerous intermodal transhipment points, freight can switch between modes when one is disrupted, increasing the resilience of the system [16]. As discussed in Verschuur (2024), however, such “modal substitutions” can be difficult to achieve at short notice. Given the greater flexibility of road freight operations, it is generally easier and quicker in an emergency to transfer freight from trains and barges to trucks than in the opposite direction.

4. Capacity.

Increasing the carrying capacity of a road, railway, or waterway usually increases its resilience by easing traffic congestion and minimising the likelihood that a route will be completely blocked. By adding redundancy, greater capacity facilitates network management, increasing opportunities to divert traffic in the event of particular routes being obstructed [17].

5. Configuration.

Rodrigue (2024) distinguishes four mode-specific configurations of transport network and assesses their relative vulnerability:

- Hierarchical meshes (road networks): mesh structure reduces the vulnerability to system-wide disruption, though concentrating freight flows on high-capacity corridors exacerbates the consequences of any disruption.
- Linear nodal hierarchy (rail networks): the need to consolidate freight into viable trainloads over competitive distance ranges tends to concentrate traffic on linear corridors, thereby increasing system vulnerability.

- Circuitous nodal hierarchy (maritime networks): much of the vulnerability of maritime transport is associated with ports that have hub and/or hinterland gateway status. Geo-strategic maritime canals, straits and corridors have also proved highly risk-prone in recent years.
- Nodal hierarchy, or "hub-and-spoke" (air transport): the "high degree of hubbing" makes air cargo networks susceptible to disruption.

This classification highlights the difficulty of generalising the relationship between this connectivity variable and resilience [18]. For this reason, it is classified as a hybrid relationship. Irrespective of the network configuration, resilience can be enhanced at the network design stage by ensuring that routes and hub locations avoid areas of high climatic and geophysical risk and that infrastructure managers have contingency plans in place to deal with transport disruptions.

6. Dimensions.

This connectivity attribute has been broadly defined with respect to the characteristics of the vehicles that can be accommodated on a network as a whole or on specific routes. It is particularly relevant to the resilience aspects of several major freight transport developments. As the net effect on resilience will be dependent on the nature of their implementation, the corresponding links have been given hybrid ratings:

- High-capacity transport: given the high cost of upgrading road infrastructure to accommodate larger and heavier trucks, these vehicles are typically confined to more limited networks. This can constrain rerouting options when particular road sections are blocked. Intelligent Access Programs, similar to that pioneered in Australia, can help to ensure that the "right truck is on the right road at the right time" during periods of network disruption (Asp and Wandel, 2023) [18].
- Intermodality: this increasingly involves the transfer of semi-trailers and high-cube containers between road and rail, which creates problems for rail networks with a relatively low "loading gauge" (i.e. vertical and horizontal clearance around the track). Typically, the loading gauge is only raised on core routes for intermodal services. This limits route diversion options on the rail network, but depending on the geographical density of intermodal transhipment points, intermodal units can be switched to a backup road service, exploiting one of the resilience benefits of combined transport [19].
- Electrification: the tighter coupling of transport networks with electrical grids to permit the decarbonisation of freight transport with low-carbon electricity will carry risks, particularly in the short-to-medium term, where the density of recharging stations for trucks is relatively low. Increased electrification of rail and possibly highway networks will also pose greater infrastructural risk, particularly from the effects of extreme weather on catenary systems. The reliability of future freight transport services will be increasingly dependent on the resilience of the renewable energy system [20].

7. Alignment.

This can be defined as the degree of fit between a freight transport network and the geographical distribution of the economic activities it serves. The distribution of these activities often changes more rapidly than transport infrastructure can be developed, causing a spatial mismatch. Many countries, for example, have legacy rail networks that are poorly structured to cater for the current needs of industrial and logistics systems that have been reoriented to the highway network. The greater the accessibility of production and logistics activities to transport networks, preferably via multiple modes, the greater the system resilience [21, 22].

8. Condition.

This is a heterogeneous attribute spanning a range of construction and maintenance standards that affect the robustness and durability of transport infrastructure. The better the condition of the network, the lower the probability of freight traffic being delayed. This connectivity attribute is, therefore, likely to be positively correlated with scheduling aspects of resilience [23].

Relationship between decarbonisation and resilience

Many governments and businesses in Central and Southeast Asia are now prioritising decarbonisation and supply chain resilience in the governance and management of logistics systems. How closely aligned are these objectives? At a planetary level, deep reductions in carbon emissions today will mitigate the future disruptive effects of climate change on supply chains and transport infrastructure, but this will be a long-term development. Governments and companies are more interested in the inter-relationship between efforts to enhance resilience and cut emissions in the short-to-medium term.

As shown in Figure 1, most of the five decarbonisation levers and six resilience levers pull in the same direction and offer synergies, though several potential conflicts exist between these objectives. The nature of these relationships will be examined from a resilience perspective.

1. Sourcing.

Supply chain "compression" is often advocated both as a risk mitigation measure and a means of reducing the demand for transport, thereby cutting transport-related carbon emissions (Choudhary et al., 2023) [24]. There is much debate, however, over the amount of added resilience likely to accrue from "reshoring and nearshoring" (e.g. Menon, 2022). As discussed earlier, much supply chain risk is country- or supplier-specific and not a function of the distance that products move. The carbon savings associated with more localised sourcing can also be small or non-existent, particularly when emissions from traded products are assessed on a life-cycle basis (McKinnon, 2024b). Minimising these life-cycle emissions often involves transporting goods long distances from low-carbon production locations (Cristea et al., 2013). This relationship [24] has, therefore, been assigned to the hybrid category. By reducing the average length of freight movements, localisation could make it harder for lower-carbon modes, such as rail, to exploit their long-haul advantage and gain market share. For this reason, relationship [25] is considered to be conflicting, with greater localisation reducing the potential for modal shift.

2. Intermodality.

Making greater use of rail and waterborne freight modes within a logistics system generally cuts carbon emissions while distributing the freight task across more transport networks. This should, at least in theory, spread the risk of service disruption [26]. The degree of risk mitigation, however, is dependent on the relative vulnerability and resilience of the lower-carbon modes. There is anecdotal evidence about service failures by individual modes in particular countries and regions, but few systematic, cross-modal comparisons of the frequency and seriousness of disruptions. The best examples of such comparisons are the "freight fluidity" assessments made in Canada and the US, which include transit time variability as a performance measure for different freight transport modes on specific corridors (Turnbull, 2014; Cedillo-Campus et al., 2019).

3. Redundancy.

So-called "safety stock", i.e. inventory used to buffer against fluctuations in supply and demand, has traditionally been used to smooth the flow of products in volatile markets. As the frequency, severity and duration of disruptions increase the natural inclination is to increase inventory levels. Building more redundancy into logistics systems in the form of excess storage, handling, and transport capacity can also offer greater protection against extreme events. Both strategies improve resilience by increasing the amount of "slack", but this can inflate the level of inventory- and property-related emissions per unit of sales. It represents an under-utilisation of assets, apparently in conflict with the effort to improve the third freight decarbonisation attribute, capacity utilisation. It is arguable, however, that its main impact is on fixed rather than mobile assets and that the environmental impact on the latter can be positive. Having extra storage space and handling capacity in warehouses and factories can make it easier to improve vehicle load factors [27] and to shift freight to slower, lower carbon transport modes [28]. Dong et al. (2017) demonstrate how incorporating modal choice decision-making into inventory and production planning can promote greater use of carbon-reducing intermodal services.

4. Scheduling.

Just-in-Time (JIT) replenishment has been widely criticised for rendering supply chains fragile and causing the under-loading of freight vehicles and an over-reliance on air cargo and trucking. Its relaxation has been advocated as both a de-risking and a decarbonisation measure, appearing to offer alignment between resilience and environmental objectives. On closer scrutiny, however, the possible contribution to both objectives is questionable, mainly on the grounds that JIT is a whole business philosophy and not simply a freight delivery mechanism. Choi et al. (2023), for example, argue that proposals to replace Just-in-Time with a Just-in-Case system of replenishment reflect "common misconceptions about JIT" and would not have avoided the types of supply chain disruption experienced in recent years. On the environmental side, easing a JIT regime can improve vehicle loading [29] and increase the use of lower-emission transport modes [30], but possibly at the expense of increasing production and warehousing emissions by a greater margin (Melo et al., 2022). This is consistent with the finding by Garza-Reyes et al. (2018) that "JIT can have a positive effect on the reduction of energy in manufacturing environments". This is a good example of boundary conditions affecting the results of an analysis. Confining the analysis to the freight transport system would suggest that relaxation of JIT pressures would yield both environmental and resilience benefits. At a logistical or supply chain level, however, greater resilience may be gained at the expense of higher total emissions.

5. Diversity.

Spreading the risk of disruption across more routes, carriers and suppliers would seem to have only a tenuous relationship with the carbon intensity of freight transport operations, except where a greater dispersal of freight flows resulted in vehicles being less well-loaded and hence emitting more GHG per tonne-kilometres. This relationship [31] is therefore deemed to be hybrid. The inclusion of energy as a diversification variable exposes a more serious potential conflict between resilience and decarbonisation in the freight sector. The current generation of diesel-powered trucks has a wide diversity of refuelling locations, minimising the risk of transport operations being disrupted by a lack of fuel. It will be many years before recharging facilities for low-carbon battery-power trucks are as numerous, making electrified freight transport systems less resilient than their fossil-fuel predecessors, at least for the foreseeable future. More generally, the decarbonisation of freight transport is likely to be fraught with risks, ranging from the geopolitics of the supply of batteries and battery materials to the local provision of reliable supplies of renewable energy. The freight decarbonising effects of the energy transition thus appear to be in conflict with the diversification aspect of resilience [32].

6. Visibility.

The resilience paper in this series (Verschuur, 2024) highlighted the importance of real-time monitoring and early alerting systems for the management of transport-related disruptions. IT systems capable of providing such services, developed by the public and private sectors, can also play a role in the decarbonisation of freight transport. They can provide a common platform for exchanging emission as well as risk data and promote the levels of information sharing required for carbon-reducing supply chain collaboration [33], intermodality [34] and energy-efficient vehicle routeing [35]. It is unequivocal that improved data-sharing and visibility mutually reinforce resilience and decarbonisation efforts.

Quantitative evaluation: choice of metrics

Quantitatively evaluating the aforementioned inter-relationships requires numerical metrics for the nineteen attributes that have been identified for the three entities. It is difficult to define metrics for these attributes for a variety of reasons:

- Inherent difficulty of translating a concept into something that is practically measurable: this is well illustrated by the "alignment" attribute of connectivity. As stated earlier, it aims to measure the extent to which the structure of a transport network is aligned with "the spatial distribution of economic activity". As explained earlier, the latter can often change more rapidly than a transport network can readjust. This partly explains why the competitiveness of rail freight services is infrastructurally impaired in some countries. It is unlikely that any single metric could measure the extent of the misalignment, particularly at a macro level. Various mapping tools, similar to those employed by Cedillo-Campos et al. (2022), could be used to measure the spatial correlation between freight-generating economic activity and the connectivity of a transport network. This could yield a statistical correlation coefficient as a metric.
- Metrics providing only a partial view of an attribute: several of the attributes, such as the "dimensions" and "condition" of a transport network, are quite broadly defined and require a multi-criteria assessment.
- Need for disaggregation by mode, commodity, sector, corridor, etc.: while some attributes can be effectively assessed at a macro-level by a single metric, others need to be mode- or commodity-specific to provide the necessary policy insight.
- Deficiencies in national freight data collection systems: analyses are likely to be heavily dependent on secondary data obtained from official freight transport surveys commissioned by governments. These surveys often track a limited number of freight variables, are undertaken infrequently and are based on relatively small samples. The choice of metrics and survey methodologies often vary by country, frustrating efforts to compare metrics internationally on a consistent basis.
- Metrics requiring separate company surveys: the measurement of some resilience and decarbonisation attributes, particularly those heavily dependent on business operations and behaviour, requires primary data from original surveys. Such surveys are likely to be less well-resourced than official government freight surveys, based on much smaller sample sizes and offer less scope for generalisation.

Despite these limitations and caveats, sets of possible metrics have been compiled for connectivity (Table 1), decarbonisation (Table 2), and resilience (Table 3), which may be used to analyse and evaluate the interaction between them.

Most of the connectivity metrics are physical network measures or the results of standard government surveys of freight transport activity. Such surveys can provide core data for the decarbonisation metrics on transport demand and modal split, but the other three attributes in this category will normally require new primary data collection. The decarbonisation metrics in Table 2 apply only to freight transport operations. To take a life-cycle perspective on freight transport emissions, additional metrics would be required to measure embodied emissions in transport infrastructure and fleets, as discussed in McKinnon (2024a). The measurement of resilience will require a mix of secondary and primary data and could benefit from the support of online commercial platforms that provide monitoring, alerting and advice on supply chain risk and resilience.

Table 1. Possible connectivity metrics

Attributes	Metrics
Extent	• Area served by the transport network (km^2) • Network length (km) for the total network and segmented by mode and class of road and railway
Density	• Ratio of the network length (km) to the area enclosed (km2) for the total network and segmented by mode and class of road and railway
Multimodality	• Modal shares of the total network length and tonne-km (%) • Ratios of modal network lengths • Comparative data on modal network densities • Density of modal interchange nodes (network km per node or km^2 per node) • Intermodal transfer frequency: the number of times goods are transferred between different modes within the network
Capacity	• Maximum tonne-km per km of the road or railway line per hour (by class of road and line and allowing for use by non-freight traffic and time of day) • Average speed of freight vehicles segmented by mode, class of road/railway/waterway, major freight corridor and time of day
Configuration	• Subjective classification by network type based on standard typology (e.g. mesh, hub-and-spoke, etc.)
Dimensions	• Maximum size, weight and manoeuvrability of freight vehicles/wagons/trains/barges permitted on modal networks
Alignment	• Statistical measures of the spatial correlation between freight-generating economic activity and the connectivity of transport networks
Condition	• Share of road and rail networks achieving internationally recognised standards (%) • Freight service reliability statistics, such as average delay times, on-time performance rates and frequency of service disruptions • Annual maintenance expenditure per route-km • Freight-related accidents per vehicle-km or train-km

Table 2. Possible decarbonisation metrics

Attributes	Metrics
Freight demand	Aggregate measures: • Total tonne-km per annum • Total tonne-lifted per annum • Total freight vehicle-km per annum, or equivalent for rail, waterborne and air cargo Disaggregated measures: • Tonne-km per capita and per unit of GDP • Tonne-km and tonne-lifted by commodity group and sector • Tonne-km and vehicle-km by geographical range (domestic/international; urban/inter-urban) • Average length of haul (tonne-km/tonne-lifted) • Handling factor (tonne-lifted/total weight of goods produced or consumed)
Modal split	• Share of total tonne-km moved by different freight transport modes (%) • Share of total tonne-lifted moved by different freight transport modes (%) • Share of total tonne-km and tonne-lifted transported on intermodal services (%) • Average length of haul by mode (tonne-km/tonne-lifted)
Vehicle utilisation	• Average share of vehicle-km run empty, or equivalent for other modes (%) • Ratio of actual tonne-km to maximum possible tonne-km (“lading factor”) • Average share of freight vehicle-km exceeding maximum legal weight (%) • Average share of cubic carrying capacity utilised (%) *Disaggregation of utilisation data by vehicle type, size and tare weight*
Energy efficiency	• Energy consumed per 100 vehicle-km, or equivalent for other freight modes (litres of fuel, Mjoules or equivalent) • Energy intensity: energy consumed per 100 tonne-km (Mjoules) *Disaggregated by mode, vehicle type, age and duty cycle (e.g. urban, long-haul)*
Carbon intensity	• Share of freight transport energy from lower carbon sources using diesel, petrol, gas oil, heavy fuel oil or kerosene as baselines (%) • Average carbon intensity of energy for types used in freight transport systems on tank-to-wheel and well-to-wheel or CO_2e basis (CO_2 per Mjoule) • Average carbon intensity of transport operation on tank-to-wheel and well-to-wheel or gCO_2e basis (gCO_2 per tonne-km) *(disaggregated by mode, vehicle class, etc.)* • Share of electrically-hauled rail freight tonne-km (%) • Density of recharging facilities for electric freight vehicles (e.g. route-km per public charging point)

Table 3. Possible resilience metrics

Attributes	Metrics
Sourcing	• Average length of haul for total freight tonnage or for tonnage by specific transport modes (tonne-km/tonne-lifted) • Share of tonne-km with origin or destination outside the country (%) • Import penetration by commodity group (% of total sales)
Intermodality	• Share of freight tonne-km moved by different modes (%) • Share of freight moved on intermodal services (%) • Spatial density of intermodal terminals (ratios of terminals to network length) • Differences in average transit time between modes (including intermodal services) • Differences in average reliability of modes
Redundancy	• Average utilisation of network and terminal capacity (%) • Average utilisation of vehicle capacity (%) • Average level of inventory: ratio of the value of inventory to sales for different commodity groups/business sectors
Scheduling	Company surveys of: • Average order lead times • Share of orders delivered just-in-time by commodity group/business sector (%) • Distribution of freight deliveries over the 24-hour cycle
Diversity	• Indices of alternative routing options for different modal networks
Visibility	• Performance standards for transport alerting systems • Share of freight vehicles with access to mobile communications (%) • Country-specific metrics used by online supply chain risk and resilience platforms

Conclusions

This paper has focused on the intersection of three freight transport policy objectives: to increase connectivity, cut carbon emissions and improve resilience. All three are being pursued in the countries of Central and Southeast Asia, though to varying degrees. As in many countries elsewhere in the world, government initiatives to make freight transport systems better connected, lower carbon and more resilient often lack co-ordination. This is partly because the inter-relationships between the three policy goals have not been adequately assessed. By mapping and examining these inter-relationships, this paper aims to increase awareness of the potential synergies and trade-offs likely to be encountered when trying, simultaneously, to meet connectivity, decarbonisation and resilience targets. It builds on the previous three papers in the series to create an integrated assessment framework within which the inter-relationships can be studied and evaluated.

The framework identifies key attributes of connectivity, decarbonisation and resilience from a freight transport perspective and considers how they are interconnected. A total of 35 interconnections were established and classified into three categories: synergistic, conflicting and hybrid. Two-thirds of them were deemed to be in the first category, suggesting that efforts to enhance connectivity and resilience and to reduce emissions are, in most cases, mutually reinforcing. Only four of the inter-relationships (11%) are likely to involve a trade-off on every occasion, while eight (23%) could be either synergistic or conflicting, depending on particular circumstances. In the case of these hybrid relationships, appropriate policy measures should help to mitigate potentially adverse effects.

This classification is based solely on the existence of a positive, negative or variable relationship. It takes no account of the relative strength of the relationship or its significance in public policy. Both are likely to vary widely, depending on national circumstances and political priorities. In customising the analysis to the needs of particular countries, some weighting of the attributes and the interactions between them would be desirable. This would require a quantitative analysis.

In this paper, assessments of the attributes and interactions have all been qualitative and verbal. Supplementing them with quantitative evaluation would entail the adoption of numerical metrics for each of the attributes and the collection of sufficient macro-level data to calibrate them. Sets of possible metrics have been suggested for connectivity, decarbonisation and resilience, many of which can be derived from official statistics currently collected in some countries. Some of the other metrics, relating mainly to resilience and decarbonisation, would need new company surveys to capture operational and behavioural data on the management of logistics systems and supply chains. If such surveys are commissioned in countries across Central and Southeast Asia and further afield, it would clearly be desirable for them to be methodologically consistent.

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Annex A. Matrices of interactions between freight transport attributes

Table A1. Matrix of interactions between freight transport connectivity and decarbonisation

		Connectivity							
		Extent	Density	Multimodality	Capacity	Configuration	Dimensions	Alignment	Condition
Decarbonisation	Freight demand	1	2		3				
	Modal shift			4			7	5	
	Vehicle utilisation				8		6		
	Energy efficiency				9	11	12		10
	Carbon intensity						13		

Table A2. Matrix of interactions between freight transport connectivity and resilience

		Connectivity							
		Extent	Density	Multimodality	Capacity	Configuration	Dimensions	Alignment	Condition
Resilience	Sourcing	14						21	
	Intermodality			16			19	22	
	Redundancy								
	Scheduling								23
	Diversity		15		17	18	20		
	Visibility								

Table A3. Matrix of interactions between freight transport resilience and decarbonisation

		Resilience					
		Sourcing	Intermodality	Redundancy	Scheduling	Diversity	Visibility
Decarbonisation	Freight demand	24					
	Modal shift	25	26	28	30		34
	Vehicle utilisation			27	29	31	33
	Energy efficiency						35
	Carbon intensity					32	

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The ITF leads the transport component of the SIPA programme (SIPA-T). The SIPA-T project helps decision-makers in Central and Southeast Asia by identifying policy pathways for enhancing the efficiency and sustainability of regional transport networks. Project outputs include two regional studies that explore opportunities to improve the connectivity, sustainability, and resilience of freight transport systems in Central and Southeast Asia.

This paper is the fourth in a series of four ITF expert working papers that collectively provide the methodological foundation for the two SIPA-T regional freight transport studies.

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