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Transportation Resilience in Times of Disaster: 2011 Earthquake and Tsunami in Japan

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Introduction

Contemporary societies are becoming increasingly dependent on energy, transport and telecommunications infrastructures. These services, essential to daily life, have over recent decades become technically complex, interdependent and costly, rendering them vulnerable and difficult to maintain. This ever-growing dependence can, in unexpected situations, lead to considerable human and financial losses, as transport systems are often among the most affected by natural disasters, even though they remain essential for rescuing victims in affected areas and supporting emergency response and long-term recovery efforts (Graham et al. 2007).

Several concepts have been proposed to study the performance of transport systems when exposed to various disturbances, ranging from frequent daily fluctuations to rare natural disasters; the term resilience appears with growing frequency in the scientific literature. In comparison with other notions such as robustness, reliability, survivability and flexibility, resilience focuses on reducing and recovering performance in the face of inevitable disturbances. In system design, daily variations must be considered and "absorbed" so as to maintain its functions. Earthquakes and other large-scale disasters inevitably displace a system from its equilibrium state. A system's ability to effectively reduce both the amplitude and duration of deviation from planned performance levels constitutes the most meaningful definition of resilience. Originally, resilience referred to a material's resistance to shock; its definition was subsequently extended to the capacity of a system, organism, species or structure to overcome a deterioration of its environment. First defined in the context of ecological systems by establishing a distinction between resilience and stability (Holling 1973), the concept was later introduced into various disciplines including organisation (Sheffi 2015), economics (Rose 2014), social sciences (Adger 2000), supply chains (Christopher 2004) and engineering (Hollnagel 2006). The notion of resilience admits several interpretations depending on the field, but most share the idea of a system's capacity to return to its initial state after severe disturbances by profoundly changing its structure (Hosseini 2016). Resilience has been widely studied in transport engineering, particularly in recent years. These studies focus notably on the intrinsic characteristics of physical networks, but few measure the resilience of interchange nodes, energy supply chains or economic and social repercussions (Reghezza-Zitt et al. 2015). Moreover, methods for assessing the resilience of major transport hubs at local or national scales are particularly lacking.

Japan has established numerous institutions and laws based on lessons learned from natural disasters that have occurred since the post-war period. Emergency interventions such as the provision of relief supplies, the management of evacuation shelters and the construction of transitional shelters are carried out in accordance with the Saigai kyūjo hō 災害救助法 (Disaster Relief Act), whose management is ensured by the Ministry of Health, Labour and Welfare (Kōsei rōdōshō 厚生労働省, MHLW). Public infrastructure is rehabilitated in accordance with three laws whose application is respectively overseen by:

• The Ministry of Land, Infrastructure, Transport and Tourism (Kokudo kōtsūshō 国土交通省, MLIT) for the reconstruction of public civil engineering structures damaged by the disaster;

• The Ministry of Agriculture, Forestry and Fisheries (Nōrin suisanshō 農林水産省, MAFF) for the reconstruction of agricultural, forestry and fishery facilities;

• The Ministry of Education, Culture, Sports, Science and Technology (Monbu kagakushō 文部科学省, MEXT) for the reconstruction of school facilities.

In the event of a major disaster, local governments may also receive special financial support. However, while rehabilitation programmes for major public infrastructure have proven effective, the mechanisms for supporting affected populations, established in 1999 following the Great Hanshin-Awaji Earthquake in 1995 in Kobe, are often judged to be slow and insufficient in comparison, as they provide only limited assistance in the economic and social recovery of individuals.

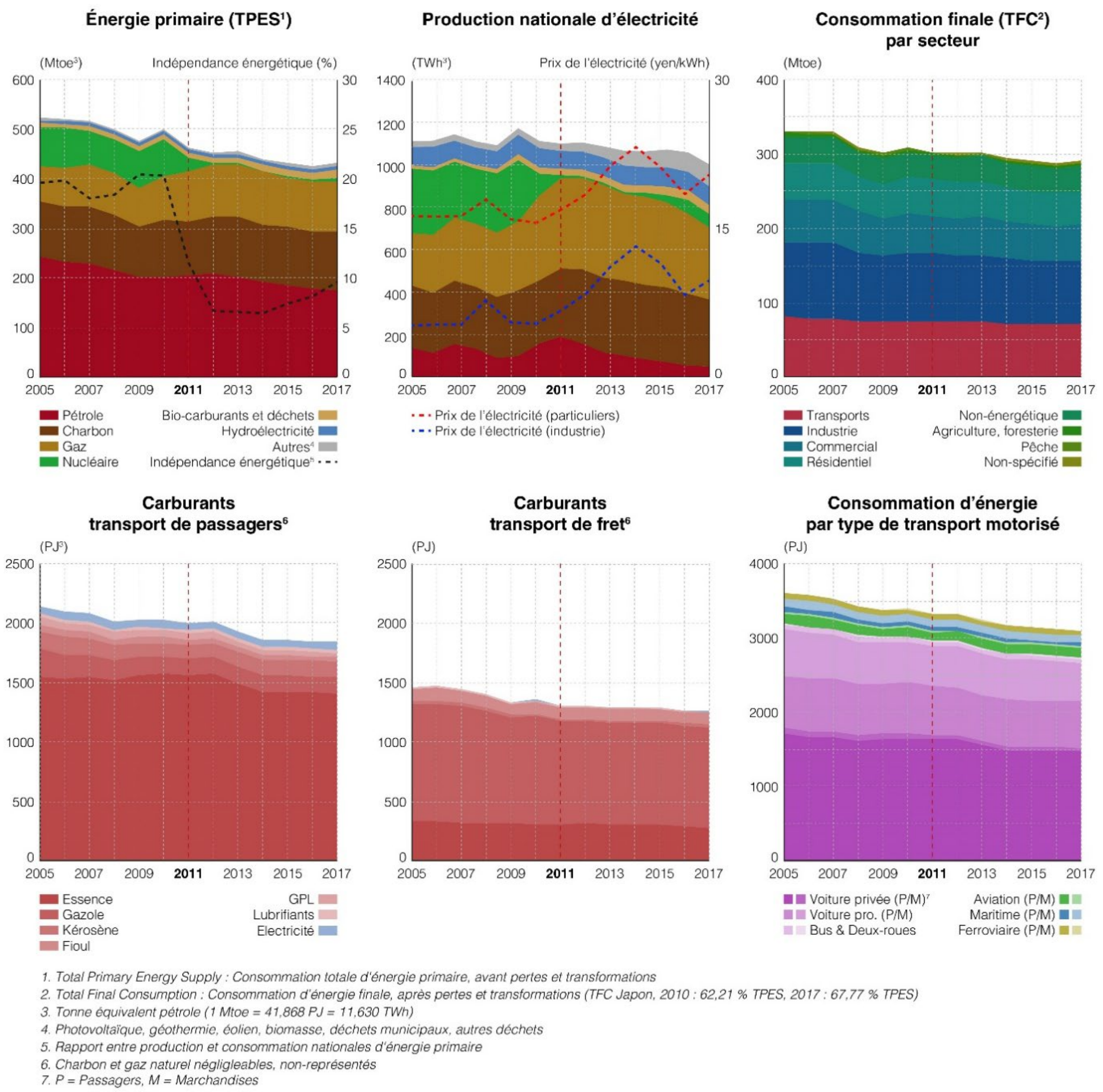
Beyond the numerous victims, the consequences of the Tōhoku Pacific Coast earthquake and tsunami on 11 March 2011 were devastating for transport infrastructure, many of which were essential for the survival of populations and indispensable for emergency interventions and were destroyed or severely damaged. The affected areas were so vast that the agencies responsible for emergency response, logistical support and civil protection suffered unprecedented losses and resource shortages, considerably reducing their operability and, in some cases, causing their complete shutdown. The situation was critical due to the collapse of bridges and viaducts, roads obstructed by cracks in their surface, landslides or debris carried by the tsunami, such that hundreds of expressway and national road sections were closed. Due to an extreme fuel shortage in several prefectures and in order to facilitate rescue operations, the authorities immediately urged the public to refrain from using private vehicles. Full service on the Tōhoku Shinkansen high-speed railway did not resume until 49 days later, while the restoration of conventional Tōhoku railway lines required, in some cases, months or even years of work. Sendai Airport and numerous port facilities were also severely affected; telecommunications were limited or interrupted entirely.

Improving the resilience of energy and transport infrastructure has been debated for several years, and this article therefore proposes an original approach by placing it in perspective through the analysis of a catastrophic situation of unprecedented scale. The first part provides an analysis of the damage and consequences of the earthquake and tsunami of 11 March 2011, an examination of the measures adopted by various ministries during three distinct phases — emergency, transition, recovery — and an assessment of past and acquired resilience capacities of transport infrastructure. The second part examines the consequences of the disaster on the energy supply for transport. The third part studies the situation of four transport networks:

road, rail, maritime and air, as well as telecommunications networks. The fourth and final part presents potential research directions on the long-term resilience of transport in the Japanese archipelago, returning for this purpose to the lessons learned by drawing a parallel between short-term destructive disaster and long-term resilience.

Part I. The Energy Question

The earthquake and tsunami of 11 March and the Fukushima nuclear accident stimulated the energy debate in the Archipelago and placed the terms "change," "community," "leadership," "vulnerability" and "resilience" at the centre of discussions (Samuels 2013). The perception of energy for citizens shifted from a simple everyday commodity to a glimpse of a highly complex, sometimes conflictual, deficient or biased system. Nuclear power was at the heart of the debate regarding changes in electricity production policy (Aoki et al. 2013), but the disaster also highlighted the dependence on automobiles and oil, particularly in suburban and rural areas.



[Figure 01: Evolution of Japan's energy situation since the triple disaster of 11 March 2011. Sources: International Energy Agency, METI. Design: Martial (2021).]

I.1. Supply of Petroleum Products

In 2010, transport — particularly road, air and maritime, which depend almost entirely on petroleum in its various forms: petrol, kerosene, diesel, heavy fuel oil — consumed 24.3% of final energy in the Archipelago and operated with 97% petroleum products. Only rail transport, almost entirely electrified in Japan, can make massive use of multiple forms of energy for electricity production. Petroleum infrastructure is therefore vital for a large part of passenger and freight transport.

Japan possesses only negligible petroleum resources on its territory and is dependent on imports. Various groups — both public and private — therefore maintain significant strategic reserves to protect themselves from the consequences of a sudden interruption in supply. However, the country has experienced a steady decline in oil consumption since 2005, owing to a shrinking and ageing population, industrial erosion, a slow but continuous fuel substitution and more stringent energy efficiency targets (Granier 2019). Natural gas is also tending to replace oil in certain industrial sectors; domestic and commercial heating is gradually being electrified. The shutdown of nuclear power plants following the 2011 earthquake nonetheless compelled Japan to increase its imports of coal and crude oil for direct combustion in its thermal power plants, raising their capacity factors.

The earthquake and tsunami of 11 March 2011 thus caused a severe petroleum shortage, significantly affecting transport and logistics in a major part of the Tōhoku and Kantō regions. Road transport became difficult due to the depletion of fuel reserves at numerous petrol stations. The remaining stations had to drastically ration their respective stocks in the face of strong demand, causing long queues. This situation continued for several weeks in various areas of Tōhoku, particularly in Miyagi and Iwate prefectures, which were still in a critical situation three weeks after the disaster. These fuel shortages severely affected numerous activities: major difficulties in rescue operations and the evacuation of most of the thousands of refugees in certain areas, major impediments to the delivery of emergency supplies to affected areas, decline or suspension of numerous socio-economic activities, deterioration of logistics functions, disruption of industrial and manufacturing supply chains, all generating considerable economic losses amounting to trillions of yen (Kajitani et al. 2013). This was the most severe shortage in the Archipelago since the oil crises of the 1970s.

The initial information made available to the public to provide an overall picture of the petroleum shortage was insufficient. While the Ministry of Economy, Trade and Industry (Keizai sangyōshō 経済産業省, METI) began publishing online information regarding measures and operations only one week after the earthquake, neither METI nor the Petroleum Association of Japan (PAJ) communicated analytical results enabling a comprehensive quantitative understanding of the situation. The government and the oil industry initially attributed the shortage to damaged refineries and port facilities. The three Tōhoku refineries affected accounted in 2011 for one-tenth of the national refining capacity of 4.5 million barrels per day. However, since the standard capacity factor of a refinery is approximately 80%, the national refining capacity could quickly regain balance by increasing production at the twenty-one other sites that remained in operation; but the location of these facilities, in the distant Kansai and Chūgoku regions, made supply to Kantō and Tōhoku difficult. Three other Kantō refineries experienced a ten-day operational shutdown, with an explosion at the Chiba refinery injuring six people. This lack of information from METI and the PAJ also left several questions unanswered regarding the measures implemented, their results and the reasons for the duration of the shortage: nearly one month in some areas. The theory of hoarding and stockpiling of oil by certain consumers was quickly dismissed due to the misinterpretation of the facts it entailed (Akamatsu et al. 2016).

Subsequent independent studies revealed that the quantity of petroleum products supplied to the Tōhoku region was insufficient, as reinforced supply from Hokkaidō had not fully compensated for the decline in deliveries from Kantō. The major shipments from western Japan announced by METI, notably from the Kansai and Chūgoku regions, in reality represented only one-tenth of the ministry's declarations. The volume transported to Tōhoku ultimately corresponded to approximately one-third of normal demand during the two weeks following the disaster. During this period, only the Sea of Japan coast ports in Tōhoku were operational. The Pacific coast ports in the affected areas did not recover partial operability until 23 March, when they received the first tankers, thereby alleviating the shortage. In terms of supply, one week after the disaster, many municipalities in Akita and Yamagata prefectures — on the Sea of Japan coast — were able to maintain a supply rate above 60% (nonetheless lower than in the initial days following the disaster), but almost no fuel could be distributed on the Pacific coast. After two weeks, the supply rate rose above 80% in most Sea of Japan coast municipalities, but severe shortages continued on the Pacific coast. After three weeks, while supply and demand on the Sea of Japan side had almost returned to normal, the supply rate often remained below 40% in certain municipalities along the Pacific coast, where the fuel shortage was still unresolved one month after the disaster (fig. 03). Furthermore, Iwate and Miyagi accounted for 80% of a significant disappearance of demand, reflecting the economic slowdown in the region. In some municipalities in Miyagi, this demand disappearance may have represented half of consumption compared to March 2010.

This critical situation served as a reminder of the indispensable nature of petroleum in contemporary transport systems. Petroleum is a public utility good supporting socio-economic activities, and the short-term suspension of its supply causes enormous economic losses. Indeed, while the cost required for the exceptional transfer of petrol from other regions of the Archipelago was estimated at between 200 and 300 million yen, the economic losses were estimated at between 150 and 200 billion yen (Akamatsu et al. 2016). The experience and knowledge gained from this event should be fully utilised to develop new preventive methods against future disasters, in order to prevent this situation from recurring during new earthquakes on the Tokai, Tōnankai or Nankai faults near Japan's largest cities. These preventive measures could include the reinforcement of petroleum product supply facilities, an increase in stocks or the design of a national support system in the event of an earthquake. Strengthened planning of logistics strategies for the emergency supply of petroleum products in specific areas seems desirable. Many industries have since refined their business continuity plans enabling them to operate in degraded mode during a disaster.

I.2. Electricity Supply

In 2011, electricity represented only 3.1% of the energy requirements of passenger transport in Japan and was almost entirely consumed by rail. While its consumption is increasing, its proportion has declined compared to the 7.2% of 1965, before the major motorisation of the Archipelago. However, this low proportion does not reflect the importance of rail in Japan. Almost entirely electrified with rare exceptions for coastal or tourist routes, and energy-efficient, the railway accounts for one-third of the national annual passenger transport volume. The decommissioning of numerous thermal power plants on the Pacific coast and of nuclear power plants throughout the country placed the Japanese electricity grid at risk of a major blackout. In the Tokyo metropolitan area, the Tokyo Electric Power Company (Tepco) being able, following the earthquake, to deliver only 31 GW — compared to 52 GW the day before the earthquake — for a demand of 41 GW, Prime Minister Kan Naoto 菅直人 approved rolling blackouts affecting 47 million people, or 37% of the population. While national production capacity was proportionally less affected — falling from 282 GW to 243 GW — it was impossible to transmit sufficient electricity from the west of the country due to limited interconnections between its ten providers, but above all because of a difference in electricity frequency between Hokkaidō, Tōhoku, the Tokyo region on the one hand and the rest of the country on the other — 50 Hz versus 60 Hz respectively — a legacy of the late 19th century when the Japanese electricity grid developed from Kantō and Kansai with German and American equipment respectively. The capacity of the frequency converters located in Nagano and Shizuoka prefectures was only 1 GW and represented less than one-tenth of the supply that became necessary after the disaster.

The rolling blackouts were intended to avoid sudden power failures that could lead to chaotic situations. Tepco divided its service area into five, then twenty-five sections based on the location of power distribution stations, then triggered power outages lasting several hours in each section in turn, while attempting to anticipate as best as possible the balance between supply and demand. With outages lasting up to three hours, certain railway lines were suspended for several days in some regions. This confused situation stranded a large number of people in rail transport, despite the advance notice of outages which, moreover, were the first since 1974 following the first oil crisis.

Over the longer term, the share of fossil fuels in the Archipelago's energy production rose from 81% in 2010 to 89% in 2016, notably due to the near-total halt of nuclear electricity production. Japan is today the third-largest importer of coal and the second-largest of natural gas, which greatly affects its energy security, its economy and its environment. Its energy self-sufficiency, already modest at 20% in 2010, collapsed to 6.7% in 2012 and remained below 10% until 2017, placing Japan second-to-last among OECD countries. This increase in fossil fuel imports also triggered a sudden rise in electricity prices which, despite a downward trend since 2014, remained notably higher in 2017.

The Electricity and Gas Market Surveillance Commission (EGC, Denryoku/gasu torihiki kanshi-tō iinkai 電力・ガス取引監視等委員会) and the Organization for Cross-regional Coordination of Transmission Operators (OCCTO, Denryoku kōiki-teki un'ei suishin kikan 電力広域的運営推進機関) were established by METI as part of the fifth reform of the Japanese electricity market in 2015. Their role is to promote the development of electricity distribution networks to ensure their cross-regional use and thus strengthen the national function of maintaining the supply-demand balance of electricity in both normal and emergency situations. For example, it is planned to triple the capacity of frequency converters by 2027, and to double the electricity exchange capacity between Tokyo and Tōhoku.

METI updated the Energy Basic Plan (energī kihon keikaku エネルギー基本計画) on several occasions with the ambition of an energy mix comprising 22–24% renewable energies; a self-sufficiency rate of 40% including a reduction in fossil fuel dependence to 56%; a 17% reduction in electricity consumption, all by 2030. To support these commitments, the government is collaborating with industry and universities in the promotion of technological and societal innovations in energy and the environment, notably through NESTI 2050 (National Energy and Environment Strategy for Technological Innovation towards 2050). The Japanese government frequently communicates on the creation of a hydrogen production and distribution infrastructure, an alternative and potentially clean energy carrier. Supply risks are potentially lower thanks to multiple means of production and furthermore represent an opportunity to decarbonise energy demand in Japan, particularly in transport. Unlike batteries, hydrogen can also be stored on a large scale and over the long term, making intermittent energy sources more relevant; it can thus represent one of the most viable energy transition options in the Archipelago in view of contemporary challenges such as the approaching peak oil and climate change.

Part II. Transport

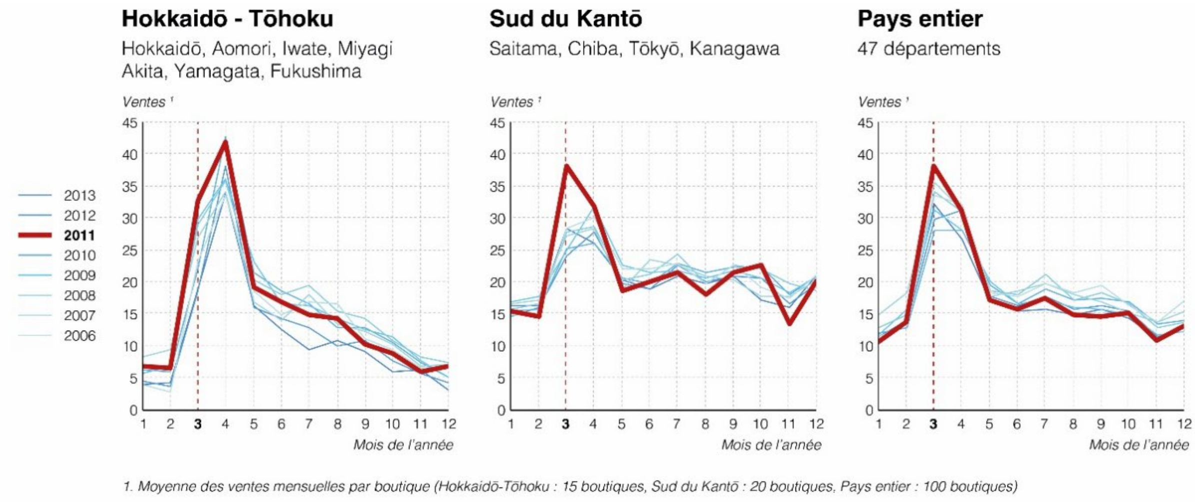
II.1. The Road Network

The road network was heavily damaged. 540 sections of toll roads, national and prefectural highways were closed. Over 400,000 vehicles, 4,198 roads and 116 bridges were destroyed or damaged, 207 landslides and 45 dyke breaches were recorded, causing floods and the carriage of debris onto roadways, thus considerably compounding the impact on the network. National Routes 6 and 45, connecting Tokyo to Sendai and Sendai to Aomori via the Pacific coast respectively, were particularly affected. Damage to the former caused the isolation of numerous people in Fukushima Prefecture; the latter was an important auxiliary route to the Sanriku Expressway (Sanriku jidōshadou 三陸自動車道), which was then incomplete. 16,000 people were cut off from the road network following the tsunami, notably in the Funakoshi Peninsula in Iwate and the town of Minamisanriku in Miyagi. The Oshika Peninsula in Miyagi was isolated following the partial destruction of National Route 398. Four hours after the earthquake, road-clearing operations were launched under the name Kushi no ha sakusen くしの歯作戦 (Operation Comb Teeth) in order to guarantee passage for rescue vehicles as quickly as possible (fig. 01). This priority mission was conducted jointly by the Japan Self-Defence Forces (Jieitai 自衛隊), the police and various prefectural and municipal organisations. It owes its name to the creation, in a first phase, of a main road corridor composed of the Tōhoku Expressway despite several damaged sections and National Route 4, which also traverses the interior of Tōhoku from north to south; in a second phase, twelve roads connecting this corridor to the Pacific coast were cleared within twenty-four hours, followed by three more in an additional two days; the third and final stage was to clear National Route 45 from Hachinohe to Sendai — 97% accessible after only one week — then National Route 6 from Sendai to Iwaki. A section of more than 50 km of the latter between Hirono and Minamisoma was suspended due to numerous landslides and flooding. After clearing and water withdrawal, a 20 km section remained suspended due to radioactive fallout from the Fukushima Daiichi Nuclear Power Plant (福島第一原子力発電所), which is located in the middle of this road section. From 22 April 2011, only authorised vehicles were allowed to travel until 15 September 2014, the date of full reopening to all vehicles. A few kilometres further south, a bypass road was inaugurated at Hisanohama on 26 February 2017 to reduce the risk of closure in the event of a disaster and thus improve the flow of emergency vehicles.

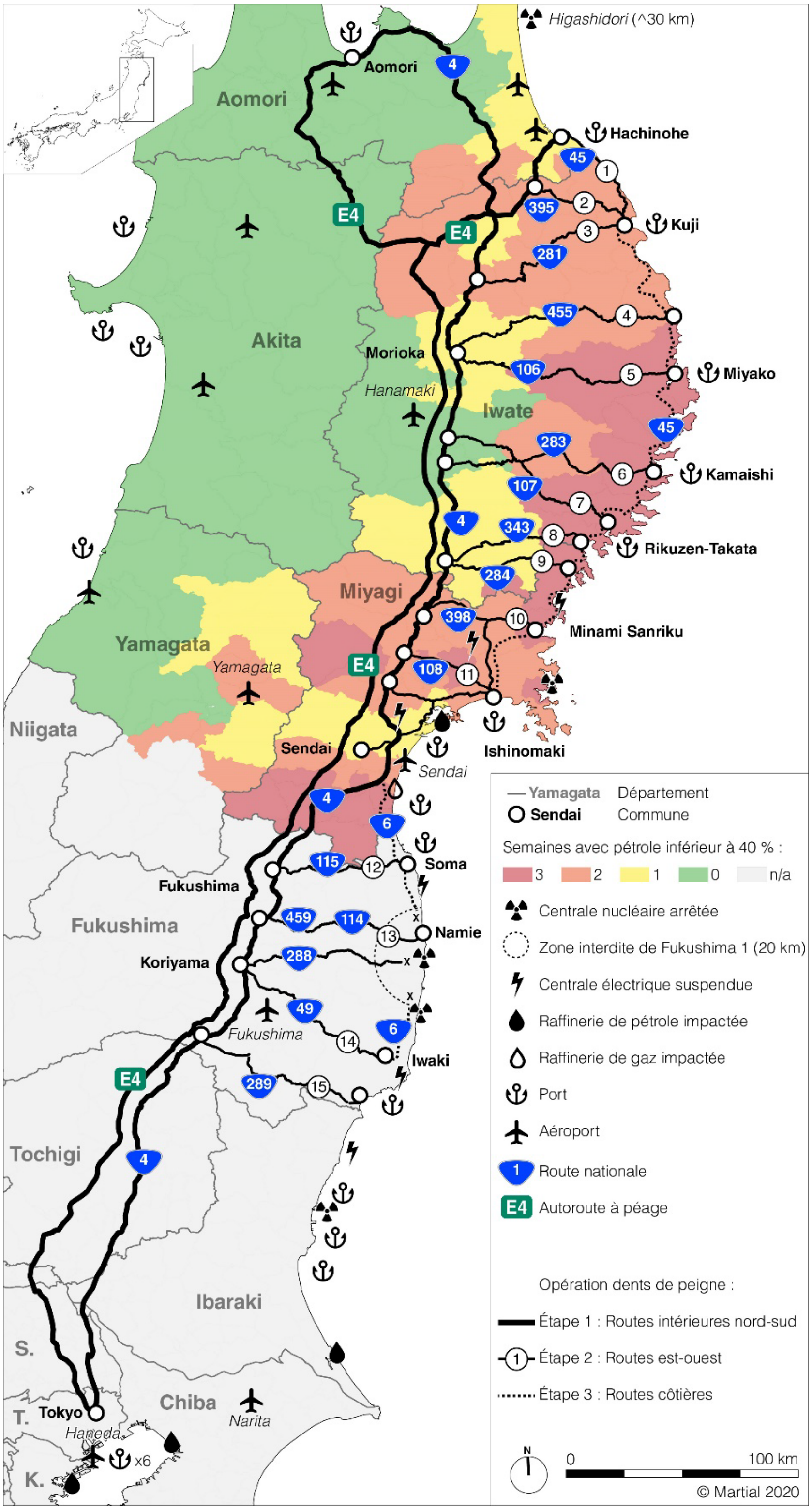
Numerous expressways under the jurisdiction of the East Japan Expressway Company (NEXCO East) were also closed immediately after the earthquake to make way for rescue vehicles, then progressively reopened to the public, from 24 March 2011 for the Tōhoku Expressway. The region's expressways were made free of charge to people affected by the disaster until 31 March 2012, in order to support the affected areas in their industry, tourism, population evacuation or return. Expressways and national roads were fully restored by the end of 2012, with the exception of certain evacuation zones and certain bridges on National Route 45. Damage remained minor in the Tokyo urban area, but a viaduct on the Shuto Expressway network nonetheless sustained significant damage and several sections were suspended for several weeks. The reconstruction of the road network in the affected areas was far more rapid and effective than in 1995, when it took more than eighteen months to fully rehabilitate Kobe's road network.

The cessation of railway services in the capital caused numerous traffic jams across the entire metropolitan area, including on main arterial roads, highlighting the vulnerability of the road network. The very large number of rail passengers who became pedestrians made traffic extremely difficult at intersections, generating according to the data collected significant gridlocks (Kiyota et al. 2014). The first traffic jams appeared around the Imperial Palace and worsened until a generalised blockage extended to the major ring roads of the urban area. 145 blocked intersections and bottlenecks were identified in the capital, compared to only around twenty on a standard day. Traffic jams were recorded until 4 p.m. the following day in some areas. Over 5 million people experienced difficulties getting home on the evening of the disaster.

This chaotic situation turned the bicycle into the only reliable means of mobility for many. Numerous commuters had no choice but to cycle home, often over distances exceeding thirty kilometres (Takada et al. 2012). Sales surged throughout southern Kantō (fig. 02) and most bicycle shops remained open until the middle of the night and the complete exhaustion of their stock. Asahi, a major bicycle retailer, reported that their regional sales doubled in the month following the earthquake. Other rural prefectures such as Yamagata also recorded a rise in sales in the days following the disaster. However, the low urban density of rural areas limited this surge to a brief episode, with journeys often too long to be made by bicycle on a daily basis. While since the 1990s, increasing numbers of commuters in urban areas have been choosing to cycle to work for various personal, environmental or economic reasons, the 11 March disaster reminded many of the reliability of the bicycle as an individual means of transport. It was already a valued possession for millions of people in post-war Japan, characterised by an exhausted transport system, roads in poor condition and chronic fuel shortages. Kobayashi Shigeki 小林成基, president of the Study Group for the Promotion of Bicycle Use (Jitensha katsuyō suishin kenkyūkai 自転車活用推進研究会), stated that the earthquake had an influence not only on the number of cyclists but also significantly modified the cycling culture in Japan. As for the areas affected by the tsunami, volunteer groups and manufacturers mobilised to send bicycles to help refugees. The Taiwanese manufacturer GIANT sent 1,000 copies of a limited-edition bicycle shinsai fukkō shienhin 震災復興支援品 (earthquake reconstruction support). These high-end, robust mountain bikes were specially designed for use by local emergency organisations and volunteers on roads no longer accessible to motorised vehicles.



[Figure 02: Bicycle sales by month from 2006 to 2013. Sources: Jitensha sangyō shinkō kyōkai, Japan Bicycle Promotion Institute. Design: Martial (2021).]



[Figure 03: Road, air and maritime transport situation after 11 March 2011. Sources: Akamatsu et al. 2016, PAJ, MLIT. Design: Martial (2021).]

II.2. Rail Transport

The East Japan Railway Company (JR East) and other railway operators immediately suspended their services following the earthquake. Station staff, drivers and conductors evacuated passengers in all areas where a tsunami warning had been issued, thereby avoiding any loss of life among passengers (Hayashi 2012).

The Shinkansen high-speed train runs on dedicated tracks, different from those of the conventional railway network. The Tōhoku Shinkansen line operated by JR East sustained significant damage at approximately 1,200 sites along some 500 km between Ōmiya and Iwate-Numakunai stations, including the tilting or collapse of electric poles, rupture of overhead wires and shear damage to viaduct piers. Only 49 days were required to fully restore service, compared with 81 days for the San'yō Shinkansen line following the 1995 Kobe earthquake, which notably caused the collapse of eight bridges. The 2004 Chūetsu earthquake in Niigata had damaged several tunnels, requiring the Jōetsu Shinkansen line to be taken out of service for over two months. This earthquake also caused the only recorded Shinkansen derailment to date, though it caused no deaths or injuries. The Shinkansen and other high-speed trains are designed not to buckle during a derailment, thus preventing the telescoping of carriages, the deadliest phenomenon in a railway accident.

Despite the unprecedented intensity of the seismic shaking on 11 March 2011, the Tōhoku Shinkansen was able to be rapidly restored thanks to three essential factors. The first was the earthquake early warning system progressively implemented over recent decades, with seismographs installed on the Miyagi Prefecture coast from 1982, which detected the seismic waves 12 to 15 seconds before they reached the Shinkansen trains running at full speed. This early detection enabled the triggering of a warning system installed in 1998, then the simultaneous activation of the power cut-off function installed in 2006, and finally the activation of the emergency brakes on all trains in service. The second factor consisted of major campaigns of new seismic design and retrofitting begun in 1996 following the Kobe earthquake the previous year. Despite the greater intensity of the 2011 earthquake, the damage was less severe and none was critical; no overturned piers as in 1995 and no collapsed tunnels as in 2004. The third essential factor was the exhaustive infrastructure restoration effort. Indeed, while the thousands of engineers of the Technical Emergency Control Force (TEC-FORCE, Kinkyū saigai taisaku haken-tai 緊急災害対策派遣) equipped with communications facilities, equipment and heavy vehicles conducted a wide range of restoration work day and night, approximately 8,500 people participated daily in the reconstruction of the railway network, comprising employees of JR East, its subsidiaries and other partner companies. The private sector thus demonstrated its importance in emergency and recovery operations. This cooperation was achieved despite thin and irregular fuel supplies. Other railway operators provided personnel for on-site inspections and restoration work, as well as material assistance ranging from maintenance vehicles to inspection equipment and fuel supply support. These various public-private collaborations are essential in a context of weakening private sector capacity. The number of construction companies has indeed declined in recent years due to reduced state budgets for infrastructure construction, Japan having reached a certain maturity in this regard. The private sector can increasingly less afford to exclusively own heavy equipment or even to hire new engineers and technicians. Restoration work nevertheless continued without interruption, enabling the resumption of service on the Tōhoku Shinkansen on 29 April 2011. It should be noted that despite the absence of damage in the regions administered by the other companies of the Japan Railways Group, these experienced difficulties in procuring spare parts produced in the affected regions, causing service suspensions on certain trains operated by the West Japan Railway Company (JR West) in particular.

Conventional lines were also severely affected, with 1,730 sites damaged by the earthquake alone and 4,400 by the earthquake and tsunami (fig. 04). These were identified along thirty-six rail segments with, once again, tilting or collapse of electric poles, track irregularities including ballast subsidence and destruction of station platforms. On the seven conventional line segments damaged by the tsunami, some twenty-three station buildings, 60 km of track and bridge piers at one hundred and one sites were swept away or buried by the waters. Intermittent aftershocks from 7 April exacerbated the damage and caused further service interruptions on lines that had already been restored. These were nonetheless able to restart within a few days.

A summary assessment is presented from north to south along the Pacific coast for clarity. The northernmost line to have suffered damage was the Ōminato Line operated by JR East. The Kita-Rias (North Rias) and Minami-Rias (South Rias) lines, managed by the Sanriku Tetsudō 三陸鉄道 (Sanriku Railway) group of the daisan sekutā 第三セクター (third sector) and separated before the 2011 earthquake by the JR Yamada Line between Miyako and Kamaishi, were among the most severely affected (Makoto et al. 2011), with significant damage to station buildings and bridges at over 300 locations. The tsunami swept away nearly 6 km of track and service did not resume until April 2014 with new diesel railcars. However, the two lines remained separated by the damaged segment of the former Yamada Line, which originally consisted of two sections: the first inland, connecting Morioka to Miyako; the second running along the Sanriku coast from Miyako to Kamaishi. While the first was only suspended for one month, the second was profoundly impacted, with more than 21 km of track flooded, four of the thirteen stations, one-tenth of the track, six bridges and ten embankments destroyed (Kazama & Noda 2012). Japan Railways proposed in 2012 that the damaged section be scrapped so that its right-of-way could be used as a transport route for a Bus Rapid Transit (BRT) system. This decision was overturned in 2015 and the section was rebuilt with the aim of subsequently transferring it to Sanriku Railway. In total, it took eight years to reopen this section in 2019, enabling the connection of the North Rias and South Rias lines and thus creating the Rias Line. It is now possible to travel directly between Kuji and Sakari stations, 163 km apart, in a little over four hours, as the line offers only local stopping services at modest speeds. The line was again suspended following the passage of Super Typhoon Hagibis in 2019.

Support and rehabilitation mechanisms have been established on a case-by-case basis for over half a century without an overall perspective and generally do not cover infrastructure belonging to the private sector. The fact that Sanriku Railway is jointly owned by local governments and the private sector explains its difficulties. The reconstruction of its railway lines required the considerable sum of 18 billion yen, representing an enormous burden for the company, which was already experiencing economic difficulties in a rural area undergoing continuous depopulation. The national government initially offered to cover 25% of reconstruction costs within the framework of existing laws, thus leaving a major share to local governments for supporting the private group. This greatly reduces the margins of manoeuvre of local authorities and does not allow for the improvement of use of damaged infrastructure. This rigidity may also discourage regular investment in day-to-day risk management in preparation for the next disaster and may even incentivise local governments to "wait for disasters" to carry out major projects, since the central government is then more willing to grant higher subsidies for reconstruction projects than for maintenance or anticipation.

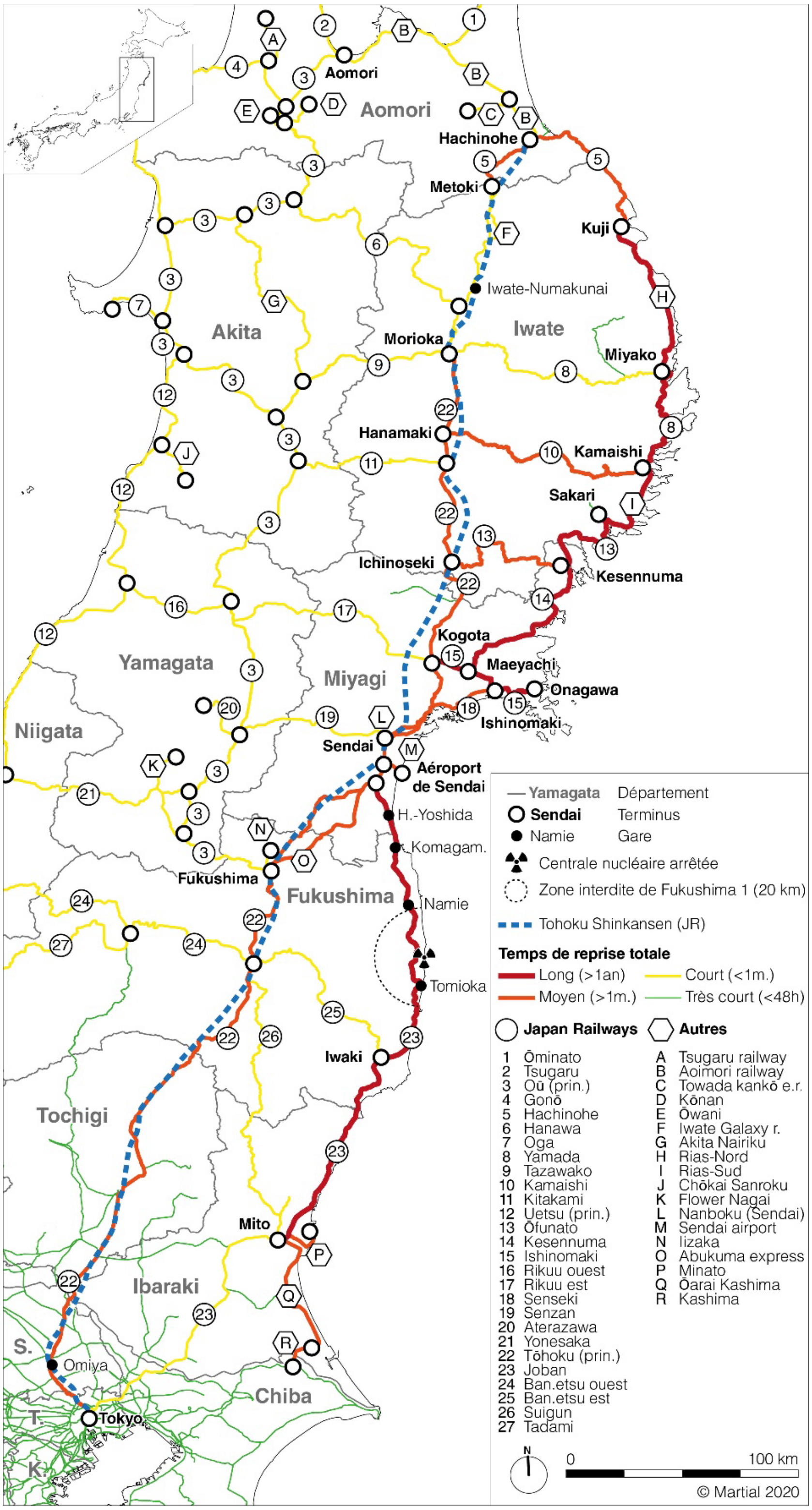
The Sakari terminus of the South Rias Line offered a connection to the Ōfunato Line, whose coastal section was severely affected. While service quickly resumed on the western 62 km section between Ichinoseki and Kesennuma, the 43.7 km section between Kesennuma and Sakari remained closed after JR East officially decided on its closure, so that its right-of-way could be used for the creation of a Kesennuma-Ōfunato BRT line. Similarly, the Kesennuma Line was partially closed and replaced by a BRT following the prohibitive costs of restoring the railway track and station buildings destroyed at, among other locations, Minami-Kesennuma and Shizugawa. Today, of the former 72.8 km line, only the 17.5 km section between Maeyachi and Yanaizu remains operated by rail. The former Kesennuma terminus is now accessible only via the Ōfunato Line. The Ōfunato and Kesennuma lines thus represent the only lines not fully reconstructed or relocated, with a total of 99 km of railway track, the majority of which has been converted to paved roads or dedicated BRT routes.

Further south, the coastal Jōban Line was one of the most affected. Most sections reopened in the days, weeks or months that followed, but the most significant tsunami damage was recorded between Hama-Yoshida and Komagamine stations, the latter being located less than 50 km north of the Fukushima Daiichi Nuclear Power Plant. This damage led to a partial relocation of the line further inland, within the framework of the city's restoration plan (Fujimoto et al. 2018). The Jōban Line also passes in the immediate vicinity of the nuclear power plant, with Futaba and Ōno stations less than 10 km away, and a section approaching to within less than 5 km. The decision to resume operations on the last inoperative 20.8 km section from Namie to Tatsuta stations was taken in 2015, with the objective of reopening the entire line by 2019. After the reopening of Tomioka Station on 21 October 2017, the line was fully restored on 14 March 2020, thus representing the completion of railway reconstruction work in the Archipelago following the earthquake (see Table 01). The conditions for reconstructing this section, extremely complex due to radioactive contamination, the prolonged existence and continuous revision of evacuation zones, the large number of evacuees and the need for storage and disposal of contaminated soil, had profound impacts on local public transport infrastructure, the availability of construction materials and labour.

	Ligne	Date de reprise totale (1)	Terminus	(5)	(6)
	Japan Railways				
	Tōhoku Shinkansen 東北新幹線	29 avril 2011	Tokyo - Hachinohe	593,1	49
1	Ōminato 大湊線	17 mars 2011	Noheji - Ōminato	58,4	6
2	Tsugaru 津軽線	15 mars 2011 (10 avril 2011)	Aomori - Mimmaya	55,8	7
3	Oū (principale) 奥羽本線	31 mars 2011 (11 avril 2011)	Fukushima - Aomori	486,3	24
4	Gonō 五能線	19 mars 2011 (10 avril 2011)	H.-Noshiro - Kawabe	147,2	11
5	Hachinohe 八戸線	17 mars 2012	Hachinohe - Kuji	64,9	372
6	Hanawa 花輪線	19 mars 2011 (11 avril 2011)	Kōma - Ōdate	106,9	12
7	Oga 男鹿線	15 mars 2011	Oiwake - Oga	26,6	4
8	Yamada 山田線	23 mars 2019 (2)	Morioka - Miyako	102,1	2934
9	Tazawako 田沢湖線	18 mars 2011 (9 avril 2011)	Morioka - Ōmagari	75,6	10
10	Kamaishi 釜石線	6 avril 2011 (12 avril 2011)	Hanamaki - Kamaishi	90,2	31
11	Kitakami 北上線	20 mars 2011 (11 avril 2011)	Kitakami - Yokote	61,6	13
12	Uetsu (principale) 羽越本線	14 mars 2011 (9 avril 2011)	Niitsu - Akita	274,4	5
13	Ōfunato 大船渡線	1er avril 2011 (18 avril 2011) (3)	Ichinoseki - Sakari	105,7	-
14	Kesennuma 気仙沼線	29 avril 2011 (4)	Maeyachi - Kesennuma	72,8	-
15	Ishinomaki 石巻線	21 mars 2015	Kogota - Onagawa	44,9	1471
16	Rikuu ouest 陸羽西線	1er avril 2011 (9 avril 2011)	Shinjō - Amarume	43,0	23
17	Rikuu est 陸羽東線	3 avril 2011 (16 avril 2011)	Kogata - Shinjō	94,4	32
18	Senseki 仙石線	30 mai 2015	Aoba-dōri - Ishinomaki	50,8	1541
19	Senzan 仙山線	23 avril 2011	Sendai - Uzen-Chitose	58,0	12
20	Aterazawa 左沢線	28 mars 2011 (9 avril 2011)	K.-Yamagata - Aterazawa	24,3	19
21	Yonesaka 米坂線	20 mars 2011	Yonezawa - Sakamachi	90,7	9
22	Tōhoku (principale) 東北本線	21 avril 2011	Tokyo - Morioka	575,7	41
23	Joban 常磐線	14 mars 2020	Nippori - Iwanuma	351,0	3291
24	Ban.etsu ouest 磐越西線	26 mars 2011	Kōriyama - Niitsu	175,6	15
25	Ban.etsu est 磐越東線	15 avril 2011	Iwaki - Kōriyama	85,6	35
26	Suigun 水郡線	11 avril 2011	Mito - Asaka-Nagamori	147,0	31
27	Tadami 只見線	14 avril 2011	Aizu-Wakamatsu - Koide	135,2	34
	Autres				
A	Tsugaru railway 津軽鉄道線	13 mars 2011	Tsugaru-G. - Tsugaru-N.	20,7	2
B	Aoimori railway 青い森鉄道線	17 mars 2011 (10 avril 2011)	Metoki-Aomori	121,9	9
C	Towada kankō e. r. line 十和田観光電鉄線	13 mars 2011	Misawa - Towadashi	14,7	2
D	Kōnan 弘南線	14 mars 2011	Hirosaki - Kuroishi	16,8	3
E	Ōwani 大鰐線	14 mars 2011	Ōwani - Chūō-Hirosaki	13,9	3
F	Iwate Galaxy railway いわて銀河鉄道線	17 mars 2011 (10 avril 2011)	Morioka - Metoki	82,0	9
G	Akita Nairiku 秋田内陸線	22 mars 2011	Takanosu - Kakunodate	94,2	11
H	Kita-Rias 北リアス線	23 mars 2019 (2)	Kuji - Miyako	71,0	2934
I	Minami-Rias 南リアス線	23 mars 2019 (2)	Kamaishi-Sakari	36,6	2934
J	Chōkai Sanroku 鳥海山ろく線	13 mars 2011	Ugo-Honjō - Yashima	23,0	2
K	Flower Nagai フラワー長井線	20 mars 2011 (9 avril 2011)	Akayu - Arato	30,5	11
L	Nanboku (métro de Sendai) 南北線	29 avril 2011	Izumi-Chūō - Tomizawa	14,8	49
M	Sendai airport 仙台空港線	1er octobre 2011	Natori - Aéroport	7,1	204
N	Iizaka 飯坂線	13 mars 2011	Fukushima - Iizaka onsen	9,2	2
O	Abukuma express 阿武隈急行線	16 mai 2011	Fukushima - Tsukinoki	54,9	66
P	Minato 湊線	23 juillet 2011	Katsuta-Ajigaura	14,3	134
Q	Ōarai Kashima 大洗鹿島線	12 juillet 2011	Mito - Kashima-Jingū	53,0	123
R	Kashima 鹿島線	16 avril 2011	Katori - Kashima-Jingū	17,4	36

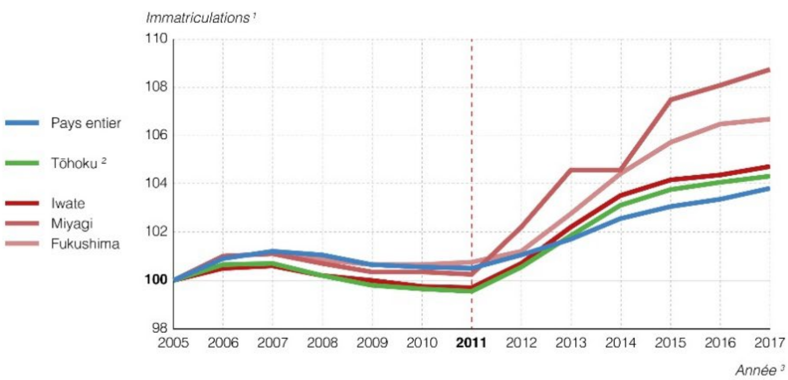
1 : Après les repliques du 7 avril 2011 si remise en service totale avant
2 : Sous la forme de la nouvelle ligne Rias
3 : Sauf tronçon Kesennuma-Sakari
4 : Sauf tronçon Yanaizu-Kesennuma
5 : Longueur de la ligne (km)
6 : Nombre de journées impactées

[Table 01: Detail of passenger railway lines impacted by the earthquake of 11 March 2011. Source: "Revive! The Railway in Michinoku: The Path of Reconstruction from the Great East Japan Earthquake." Design: Martial (2021).]



[Figure 04: Passenger railway lines impacted by the earthquake of 11 March 2011. Source: "Revive! The Railway in Michinoku: The Path of Reconstruction from the Great East Japan Earthquake." Design: Martial (2021).]

The scale of the seismic disaster, the demographic upheavals in areas affected by the nuclear disaster and the uncertainties arising from radioactive contamination continue to make the operation and planning of local transport difficult. While most local transport was paralysed following the disaster, others were able to provide essential means during the initial emergency evacuation and then during the transition period, in order to meet the changing demand induced by the updating of the evacuation zone. New bus lines, BRT services and also on-demand shuttles were established. BRT systems are often better suited to passenger transport in low-density rural areas but do not serve specific destinations such as hospitals or schools, unlike municipal buses, which are slower but have more stops at shorter intervals. Thus, an NGO was able to coordinate access to public services, supermarkets and other daily destinations through various volunteer transport services, contributing to the mobility of evacuees, notably in Ōfunato. The limited supply of petroleum products had less effect on taxis and buses in the region than on private vehicles: taxis predominantly run on liquefied petroleum gas and buses were able to rely on the Japan Bus Association (Nihon basu kyōkai 日本バス協会) to transport fuel from their reserves scattered across the country in an emergency. However, since these new transport services are largely dependent on funding released in 2011 by MLIT for a ten-year period until the end of 2020, their long-term status appears precarious. Part of this budget was, for example, allocated to connect refugee villages with a continuously declining population, but bus companies appear slow to adapt their business models to the end of government allocations. It should also be noted that the Tōhoku region has a strong mai kā マイカー (car culture, from the English "my car"), with public transport networks proving inadequate for the dynamics of urban sprawl. The vast majority of people therefore repurchased a private vehicle as soon as possible and did not wish to or were unable to change their mobility habits (fig. 05). The dynamism and density of Sendai's transport remain a counter-example for the region: most of the railway lines closed following the disaster had, like most provincial lines, a fragile economic health. Rail transport is indeed an investment requiring high urban density to hope to achieve profitability. The BRT systems put in place offer a high-quality service for far lower investment, but they represent only one solution among others at a time of emerging smart grids and smart communities, which offer various on-demand transport solutions in the longer term.



1. Base 100 en 2005
2. Aomori, Iwate, Miyagi, Akita, Yamagata, Fukushima
3. Immatriculations comptabilisées au mois de mars

[Figure 05: Evolution of the number of registered motorised vehicles in Japan from 2005 to 2017. Source: Ji ken-kyō (AIRIA). Design: Martial (2021).]

The number of registered motor vehicles did not experience a notable decline in 2011 despite the 400,000 vehicles damaged or destroyed, indicating near-systematic replacement within the year. While the increase in registrations is relatively continuous at the national level, an inflection should be noted in 2011 in Tōhoku, particularly in Miyagi and Fukushima prefectures, which suffered the most from the marked decline in the service level of public transport.

II.3. Air Transport

The critical state of road and rail transport transformed air transport into the most practicable and effective solution for accessing the affected regions for at least the twenty days following the disaster. Moments after the first seismic tremor, Sendai Airport, located just a few hundred metres from the coast and lacking sufficient dykes and breakwaters, was struck head-on by the tsunami. The two runways, the apron and the taxiways were submerged by several metres of water and the ground floor of the terminal was almost entirely flooded. However, as the approximately 1,200 passengers and staff had had time to take refuge on the upper floors, no deaths or missing persons were reported within the airport grounds. The backup generators and the ground radar of air traffic control were destroyed. Under normal conditions, Sendai Airport constitutes a hub for Tōhoku air traffic, with the other regional airports generally handling only a limited number of passengers and freight. Its restoration therefore constituted an absolute priority for the authorities.

The United States Forces in Japan provided personnel and resources as part of the crucial humanitarian aid Operation Tomodachi (Tomodachi sakusen トモダチ作戦). It took place from 12 March to 4 May 2011, involved 24,000 American military personnel, 189 aircraft, 24 warships and cost 90 million dollars. The majority of American military bases in the Archipelago were mobilised and conducted joint operations with the Japan Self-Defence Forces (Wilson 2012). As the American military constantly requires a large quantity of fuel to operate, it was able to draw on its considerable reserves. While firefighters and volunteers generally focused on assisting individuals, the mobilisation of military forces enabled not only evacuation and the construction of emergency shelters, sanitation facilities and showers, but also the reopening of Sendai Airport from 15 March for humanitarian flights, which then became a hub for emergency supply transport, despite the approximately 2,000 damaged vehicles and 370,000 m³ of debris carried onto its grounds. Helicopters arrived on the fourth day after the disaster and US military transport aircraft on the fifth, after the installation of temporary air traffic control equipment directly on the runway. The airport reopened on 13 April for commercial flights, only 32 days after the disaster, and returned to normal operation on 25 September 2011.

Emergency alternatives for civilian air transport were nonetheless necessary until the complete restoration of Sendai Airport. The authorities chose to exploit the surplus capacity of certain Tōhoku regional airports, thereby maintaining a broadly comparable level of service after the disaster, a solution that consisted of diverting flights from the inoperable Sendai Airport to Hanamaki, Fukushima and Yamagata airports, leading to a substantial increase in their passenger numbers. Yamagata Airport, thanks to its proximity to the city of Sendai, its low radioactive contamination and its minor damage, multiplied its passenger numbers by fifteen during the twenty days after the disaster. It went from 20 to 60 aircraft per day, while Hanamaki and Fukushima went respectively from 20 to 100 and from 25 to 85 (Aratani et al.

2013). Despite the surprising speed and degree of flexibility of these changes, certain operations reached critical thresholds, such as the management of aircraft and helicopter parking, as well as fuel supply. Emergency management officials attempted to adapt Yamagata Airport's transport capacity as best as possible to growing demand, but it was nevertheless not possible to guarantee a flight to all passengers arriving at the terminal during the first days. The remarkable surge in demand for ground transport to the airport had repercussions on regional public transport: added to the unavailability of railways, the new role conferred on Yamagata Airport weighed on Tōhoku's ground transport system.

Haneda and Narita airports serving the capital, by far the busiest in the Archipelago, suspended their activities within minutes of the first seismic tremor, despite the absence of major damage to runways or terminals. Thus, of the approximately 500 and 250 daily aircraft handled by the two airports respectively, 86 were diverted. A veritable crossroads in aerial assistance during Operation Tomodachi and the evacuation of American families, the Yokota Air Base near Tokyo also admitted 11 American civilian aircraft. In total, 8,500 passengers encountered difficulties getting home.

With the exception of Sendai, the country's airports were able to reopen from 14 March. Nonetheless, due to fears regarding the nuclear accident, several airlines suspended their service to the capital from 15 March. While each airport has regularly updated earthquake resistance measures, the 2011 disaster illustrated the inadequacy of anti-tsunami measures, demonstrated the importance of airports during a disaster and helped draw several lessons (Hanaoka et al. 2013). First, communication and cooperation between the various airport organisations during an emergency situation must be improved and simplified to avoid excessive confusion. The 2008 Iwate-Miyagi Nairiku earthquake provided the opportunity for Hanamaki Airport staff to work on these issues for three years until the eve of the disaster, allowing them to rapidly share their feedback throughout the Archipelago. Others undertook similar efforts on air traffic control, parking allocation and refuelling. The Japan Civil Aviation Bureau (JCAB) was then able to offer continuous training and take charge of air traffic control; local government becomes the administrator of the airport; airline operators and airport facility managers can then manage a series of operational tasks even in emergencies. Furthermore, the diversification of aircraft fuel sources and the securing of supply routes rely on coordination between suppliers, fuel distributors and airport administration.

Cooperation between aircraft operators is crucial for ensuring rapid decision-making, which is paramount during the initial phase of a disaster. Government aircraft, those of the Japan Self-Defence Forces and the Japan Coast Guard, US military aircraft, medical intervention helicopters and media helicopters, and commercial aircraft providing emergency transport, all played an important role. Naturally, each involved organisation managed the situation by transmitting its information to its respective headquarters. It was difficult for the disaster response headquarters to give specific and detailed instructions to the aviation department, as a general administrative organisation is rarely involved in these activities. Each organisation, knowing only partially the actions of the others, had difficulty coordinating. The immediacy of a disaster inevitably leads to actions undertaken quickly and independently by each body, but a mechanism for sharing a minimum of useful information such as activity statuses was probably lacking. The establishment of an aeronautical operational team during the transition and recovery phases within the disaster response headquarters would have enabled more effective crisis management, with a system featuring a clear chain of command allowing the sharing of information, the implementation of measures and the transmission of instructions between organisations. Communication between aircraft during the disaster played an essential role in the simultaneous launch of numerous flights by several organisations towards a specific area. Although many rules exist in normal times to ensure flight safety, securing a common method of communication between aircraft and the ground station was invaluable for gathering information and conducting rescue activities safely.

The disaster served as a reminder of the need to transform airports into crisis management and supply bases. The nature of air transport, devoid of a continuous physical network and connected to national and international destinations, confers upon it a resilience superior to road and rail networks. The significant margins in airport facility utilisation rates demonstrated the importance of surplus capacity and certain redundancies for absorbing part of the severity of a disaster's shock. However, the 2011 management suggested a multipurpose use of airport facilities for occasional crisis situations, ensuring for example sufficient aircraft parking space, additional temporary fuel storage, temporary lighting for night-time work and sorting and storage facilities for relief supplies.

II.4. Maritime Transport

Japan, an island nation, can count on the extent of its maritime zone, its 34,000 km of coastline and its industry largely located in coastal areas, in proximity to numerous port facilities. The approximately 1,100 commercial ports and 3,000 fishing ports account for 99% of the tonnage of goods transported in the country. However, with waves reaching up to 9.5 m as in the port of Ōfunato, the tsunami devastated a significant number of these facilities all along the Pacific coast. The port of Sendai was struck by the tsunami just minutes after the first seismic tremor; the ports of Minamisanriku and Rikuzentakata were submerged. The tsunami damaged or destroyed a good number of dykes and breakwaters, including the world's longest, inaugurated in 2009 in Kamaishi Bay. The Miyako dyke, 2.5 km long, was deteriorated at several points. These protections nonetheless demonstrated their effectiveness in delaying and lowering the height of the wave in certain areas. From Aomori to Ibaraki, numerous containers were scattered across quays and the shoreline. Combined with the various vehicles, vessels, buildings and timber carried along, they became major obstacles to safe passage in the various channels and anchorage areas (Kumagai 2013). Maritime rescue was therefore limited until berths enabling unloading could be secured. After the tsunami warning was lifted on the evening of 13 March, the clearing of the various channels and port facilities could begin the following morning. Priority for clearing work was given to the ports of Miyako, Kamaishi and Sendai-Shiogama, the largest port in Tōhoku, with the primary objective of transporting emergency supplies. Clearing was then extended to other major ports. The first vessel carrying essential goods was thus able to enter the port of Kamaishi on 16 March. The first tanker was able to berth at the port of Sendai-Shiogama on 21 March, thus alleviating the fuel shortage in the region. On 23 March, the passages of ten ports were secured, enabling a more substantial flow of relief by sea.

The economic effects of port destruction were felt throughout the Tōhoku region, especially in Miyagi Prefecture. Its Sendai-Shiogama port complex, which represents approximately 40% of the region's international trade, is composed of four ports: Ishinomaki, Shiogama, Matsushima and Sendai. While Sendai-Shiogama partially reopened on 16 April, the volume of containers exchanged fell by more than half in 2011 and it was not until 2015 that it recovered its 2010 level. Over 300 fishing ports and nearly 20,000 of their boats were damaged or destroyed. Only 115 were able to resume all their activities within the two years following the disaster; at the end of 2019, 35 of them still had limited operability.

The experience of the Pacific coast ports during the 2011 disaster offers multiple lessons for ports worldwide. The scale of the damage not only served as a reminder of the vulnerability of an economy, even a technologically advanced one, but also that significant long-term traffic losses can persist despite the restoration of damaged infrastructure. This poses lessons for port facilities confronted not only with the threat of natural disasters but also with sudden events of human origin such as wars, embargoes or general strikes. Sendai-Shiogama demonstrated that pre-disaster mitigation or preventive actions constitute the best option for addressing seismic risks, through soil reinforcement by densification or compaction, the seismic design of port structures, the modernisation of intermodal facilities such as bridges and, of course, the installation of dykes and breakwaters. In the face of the scale of the 2011 tsunami, none of these measures proved sufficient. These lasting losses are intrinsic to the conditions of intense port competition, both national and international. This long-term perspective presents an important lesson for disaster planners, especially concerning facilities as capital-intensive as ports. The disruption caused by major sudden damage can lead in the short term to a fall in port revenues and in the long term to a weakened competitive position. Classical models of the economic consequences of natural disasters assume a full recovery once physical damage is entirely repaired. Yet 11 March 2011 demonstrated their obsolescence and the need for new models to address the potential economic repercussions that would persist beyond the period of physical reconstruction.

II.5. Telecommunications

Initial damage assessments and rescue operations require high-performance communication tools, making telecommunications networks crucial during a disaster. Services in the affected areas are subject to demands far exceeding normal levels, placing operators in an emergency operating situation even in the absence of physical damage to the network. The 11 March disaster opened a vast domain of performance improvements in critical situations. Seismic reinforcement of buildings and IT equipment had previously helped reduce damage, but connections had for the most part not been upgraded. These were again damaged by the considerable geological stresses during an earthquake, such as liquefaction, ground deformation and landslides.

Telecommunications facilitated the implementation of an earthquake early warning system offering users a few seconds' notice before the first tremors, allowing them to take cover or flee buildings. In the first instance, network maintenance is essential for this initial protection, then during alerts for possible aftershocks. The regular earthquakes in the Archipelago represent so many opportunities for operators to improve and maintain their respective networks under degraded conditions. These prior learning opportunities enabled them in 2011 to maintain a globally satisfactory level of performance given the scale of the disaster, despite significant outages.

The effects on communication networks beyond the Tōhoku region were limited. Their usage, multiplied by 8 to 9 in the case of the Tokyo region, did not cause critical problems unlike in other disasters, for example thanks to the implementation of call restrictions and the transfer of most communications to an information service on people affected in the disaster areas. The optimal protection of the entire network remains extremely delicate, but notable efforts on redundancy and emergency intervention planning on the physical network showed marked improvements in system recovery compared to the 1995 Kobe earthquake. The latter had in its time provided numerous lessons on the possibilities for improving telecommunications resilience.

One and a half million fixed telephone lines went out of service between 11 and 13 March. Although half of them were repaired by the 14th, it took nearly two weeks to restore 90% of service. More than half of NTT's 1,800 buildings were affected by the earthquake or tsunami, most by power outages. These rely on batteries capable of operating for 24 to 48 hours, which explains the proliferation of outages until 13 March. Damaged roads hindered the rapid deployment of portable generators to recharge and take over from the batteries. Improvements in underground seismic designs housing the cables had nonetheless made the fixed network more robust than in 1995 (Kwasinski et al. 2012).

Significant outages affected wireless communication equipment, again due to multiple power failures and operations centres damaged by the tsunami. The batteries of base stations are even more vulnerable given their shorter autonomy of approximately eight hours, leading to the shutdown of thousands of transmitters on the day of 11 March. Operators ensured emergency coverage through hundreds of satellite phones in the most affected areas, normally used in remote regions. They also opened their Wi-Fi access points, restricting bandwidth to basic communications. Transmitters were gradually restored to service but more than a thousand remained inoperative in early April. In this difficult context, the success of the instant messaging application LINE can be explained by its use of the Internet, less disrupted than telephone networks, for communication.

A significant drop in Internet searches was noted at the time of the earthquake, again due to power outages, but the situation returned to normal within an hour. The network subsequently experienced peaks at approximately 200 times normal traffic. Being composed of a dense mesh, it held up well in comparison with the outages observed on its fixed and mobile counterparts. Only a small portion of the approximately twenty undersea cables connecting the Archipelago to the rest of the world was damaged, causing only a small number of the thousands of traffic routing centres in the Archipelago to go out of service. Several companies also encouraged teleworking in order to spare their employees overly difficult commutes.

While the overall performance of the various telecommunications networks remained adequate given the disaster, areas for improvement emerged. A finer understanding of failure modes and emergency intervention planning is possible for developing an even more resilient system. The deployment of the fibre optic network in response to growing demand for connection speed and data transfer volume has since been carried out with more robust seismic installations. NTT also announced an investment of 600 billion yen over six years in solar and wind energy production facilities and battery systems for essential neighbouring facilities such as hospitals and factories, in the event of power outages during a disaster or other emergencies.

Part III. Conclusion

This article analyses the transport situation and the reaction of the authorities following the earthquake and tsunami that occurred on 11 March 2011, whose disastrous consequences form in retrospect a critical stage in the development of more resilient infrastructure. Numerous lessons have been drawn to strengthen the capacities of transport infrastructure. Transport is by nature an interdisciplinary field and this disaster situation has only highlighted the need for a less segmented approach to their respective planning and models. While studies on sustainable development have multiplied in recent years, those on transport remain comparatively thin. However, four broad categories of research on sustainable transport can be identified (Badassa et al. 2020). The first concerns the definitions, indicators and parameters of sustainability for a sustainable transport system; the second focuses on the evaluation of socio-technical systems; the third focuses on the performance indicators of urban transport; and the last is based on the analysis of the sustainability of cities and intercity transport services.

The great dependence on automobiles and petroleum, resulting from continuous urban sprawl in the Archipelago, was highlighted by the various shortages, thus fuelling the debate on the question of urban sustainability in Japan and konpakuto shiti コンパクトシティ (compact cities). These were initially addressed in the context of the country’s depopulation, notably with the genkai shūraku 限界集落 (marginal settlements), communities in a state of advanced depopulation and at risk of disappearing when more than half the inhabitants of the village are over 65.

Another related subject, the shōmetsu kanōsei jichitai 消滅可能性自治体 (possible extinction of local municipalities) refers to the hundreds of municipalities identified as likely to lose more than half of their young women and therefore considered on the path to extinction. The government is attempting to halt this phenomenon through regional revitalisation (chihō sōsei 地方創生), a series of policies aimed at improving the vitality of these regions, notably through new means of transport. The compact city strategy predates 2011, but the disaster accelerated numerous measures aimed at revitalising town centres or improving urban centres and public transport networks. As Japan’s population is likely to decline further in the coming decades, the judicious reduction of urban sprawl is an urgent challenge and must be carried out in correlation with more prudent land-use planning.

Many places affected by the tsunami had experienced catastrophic damage on multiple occasions in the past. Many were rebuilt in a similar manner, relying notably on several hundred kilometres of ever-higher and more robust dykes, subject to numerous controversies, as are the relationships between the government and construction companies, sometimes judged to be incestuous. The relevance of these dykes is indeed a subject of debate, as technical, economic and security perspectives must be tempered by social, landscape and ecological considerations. This decision is criticised by many, who proclaim the need not to repeat past errors of resettlement in dangerous areas, with residential zones needing to be placed at a safe distance and elevation. Flood-prone areas, for their part, should be considered as natural land, agricultural zones or industrial zones around fishing ports.

These decisions often fall to local governments. It is internationally recognised that local governance represents the front line of intervention in the event of a disaster, with the success of transition and recovery depending on strong leadership (Berke et al. 1993). National agencies play an important role in disaster preparedness through the establishment of warning systems, evacuation plans and continuous education, but local governments remain the principal bodies responsible for building standards and land-use regulations aimed at mitigating disaster damage as far as possible. Japan follows this process. During a disaster, the Prime Minister may issue directives as head of the Bōsai jōhō 防災情報 (Disaster Management Centre of Japan, under the MLIT); these derive from the saigai taisaku kihon hō 災害対策基本法 (Basic Disaster Countermeasures Act) and are revised on the basis of lessons learned from the 1995 Kobe earthquake. However, there is no single national entity to directly control disaster prevention and response measures. The heads of these administrative organisations, local governments and public bodies may take the actions deemed necessary under these directives. Municipal and prefectural disaster management councils are required to prepare their respective plans taking into account the local context on the basis of the basic countermeasures plan. In practice, the Prime Minister's authority is unlikely to be effectively exercised because the various organisations and local governments are not part of his direct chain of command (Suzuki et al. 2013). Emergency responses, which should in principle be carried out by the respective local authorities, make the Prime Minister's central command difficult and slow.

Among the lessons drawn at the national level, the Committee for the Promotion of Disaster Management of the Council responsible for reviewing disaster prevention measures (Bōsai taisaku suishin kentō kaigi 防災対策推進検討会議) proposes interventions on three essential points: review of design codes for facilities and preparation of rehabilitation manuals; formulation of these rehabilitation plans during normal periods without disasters; strengthening of the spirit of cooperation between national and local governments, promotion of prior agreements with private companies. These three points must address certain shortcomings noted during the 2011 disaster, namely the establishment of more flexible financial arrangement mechanisms, the conclusion of agreements with the private sector before a disaster, the formation of expert teams at the national level, the construction of even more resistant infrastructure and the establishment of a clearer priority for key infrastructure to be rehabilitated. The national government also undertook several innovative measures concerning transport within the framework of the promotion of smart grids and smart communities, notably with better integration of topographic, demographic and social data.

While smart grids operate according to a top-down approach, smart communities propose a bottom-up approach involving citizens, public bodies and businesses in the construction of less energy-intensive and polluting lifestyles for increased long-term resilience; but these smart grids can also apply to very short-term responses in emergency situations (Nakagawa et al. 2004). Various initiatives have been launched over time and promoted by the Ministry of the Environment (Kankyō daijin 環境大臣, MOE), METI and MLIT. Noteworthy among these are the Eco-Town Model Project launched in 1997, the Environmental Sustainable Transport Model Project (EST) in 2004, the Eco-Model City Project (EMC) in 2008 and the Future Cities Initiatives in 2011 (Lecler et al. 2015).

Distinguishing the authorities' response into three distinct phases — emergency, transition, recovery — highlights the challenges to be met in each phase (Nakanishi et al. 2011; Yoshida 2012). The emergency phase required immediate repair of infrastructure and a capacity to adapt to constantly changing transport needs. While most national initiatives showed some weaknesses, local interventions generally worked well to address priority problems. The rescue of people, the transport of emergency supplies and the restoration of roads were achieved at unprecedented speed thanks to various local initiatives relying on dense information and business networks. Local leaders played an important role in gathering intelligence on the various transport demands and in routing volunteers. The transitional phase demonstrated the importance of the adaptability of transport services in order to support individuals in resuming a normal life as quickly as possible. Community engagement and social capital were also essential for decision-making in an abnormal, complex and resource-limited context. The recovery phase serves as a prelude to the design of a more resilient community, capable of more effectively anticipating the next disaster through increased interoperability and redundancy of transport infrastructure.

While Japan regularly suffers from natural disasters, it accumulates the knowledge and technologies necessary to anticipate and prepare for them. The strengthening of resilience capacities nonetheless remains a challenge, not only in areas subject to past events demonstrating a memory that is sometimes too short (Sato et al. 2017), but even more so in order to apply them at a national, or even international, scale. It is also necessary to raise public awareness that the majority of damage and deaths during a disaster results from architectural and urban planning. In light of the existing literature, further research on how these challenges may be overcome in practice will be crucial for supporting the planning of resilient transport infrastructure (Faturechi et al. 2014). Over the longer term, the disaster may serve as a violent reminder of the fragility of our infrastructure, which needs to be reconsidered. Indeed, while the oil crises triggered a first energy transition that was constrained and accelerated by supply difficulties and the surge in prices following political decisions, Japan was pushed to its energy limits on 11 March 2011 by physical reality. While it has succeeded in prospering economically despite strong energy, geographical and demographic constraints, the triple disaster reminded it of the strong correlation between energy and the economy, and presented an opportunity to accelerate an energy transition that would likely prove beneficial in view of the global peak oil, anticipated supply difficulties and climate change.

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