Introduction

Refrigerated transport is an essential link in the cold chain and aims to supply the consumer with safe, high-quality perishable goods. The goods concerned are perishable foodstuffs or non-food goods such as pharmaceuticals, flowers, plants, works of art, chemical products, etc. Frozen goods are transported at a temperature of –18ºC or lower, chilled goods at a temperature above the freezing point. Some goods are also transported at controlled temperatures above 15°C (e.g. cocoa, coffee, flavours, certain fruit and vegetables, certain pharmaceuticals).

Food transport refrigeration is a critical link in the food chain, not only in terms of safety by properly maintaining the temperature of the transported goods, but also through its impact on energy consumption or CO₂ emissions. One of the greatest issues in refrigerated transport is the high dependency on oil for both refrigeration and motion purposes. Refrigerated transport equipment has been progressively improved over the past 60 years in line with the development of food trade worldwide.

Distances between production areas and consumers are increasing. A large amount of goods is transported from the southern to the northern hemisphere and vice versa, in order to benefit from seasonal production. Even if such exports are now criticized in some cases, transport activities will continue to expand.

Currently, there are around 4 million refrigerated vehicles in service worldwide, including vans (40%), trucks (30%), semi-trailers or trailers (30%). According to a recent study, global road freight transport is expected to grow 2.5% per year until 2030. This clearly illustrates the importance of refrigerated transport worldwide. In addition, temperature-controlled pharmaceutical freight is expected to grow more than 20% per year. In order to keep pace with this expansion without raising its impact on the environment, the refrigerated transport sector will have to meet several scientific and technical challenges, with a focus on vehicle design, refrigerating equipment, refrigerant issues, food safety and management and logistic aspects.

Vehicle design optimization

Even though vehicle energy consumption has been significantly reduced over the past 20 years, there are still opportunities for further improvement, in particular as far as refrigerated equipment is concerned. In order to address the challenges of environmental performance and sustainability, innovation is being introduced to refrigerated road transport in several directions. Inspiration is often derived from other refrigeration fields then adapted to transport, which has unique features and requirements.

- **Insulation:** the search for better insulation focuses on the thermal conductivity of materials. With changes in foam-blowing agents over the past 10 years, the quality of insulation for refrigerated bodies has deteriorated somewhat. New insulation materials such as new types of foams, vacuum panels and aerogels have recently appeared on the market. Their application in refrigerated transport needs to be tested. Insulation should also be improved by the use of sophisticated composite structures where protection from thermal radiation and reflection can improve the insulation characteristics. The reduction of thermal bridges should also be investigated, particularly in bulkheads.

- **Thermal losses:** door openings are the main source of thermal losses in trucks, especially during delivery operations, and air losses from the body are known to be a major cause of energy inefficiency. In other refrigeration systems such as display cabinets or cold rooms, airflow systems or automatic doors are commonly used to reduce cold air losses. This experience should be adapted to refrigerated trucks in order to understand the efficiency gains that could be achieved. The joints used for insulated bodies have been improved, but there is still room for improvement in the closing of lateral doors and the ageing of joints for example.

- **Multi-temperature equipment:** multi-temperature equipment allows energy savings with the use of a single vehicle to deliver goods at different temperatures in the same operation to the same place. For more than 15 years, their market share has been growing, and this technology represented 20% of in-use equipment and 30% of new equipment in France in 2009. The performance of this equipment can be improved further, and testing and sizing should be harmonized.

- **Aerodynamics:** more than 15% of the energy consumption of a truck can be caused by poor aerodynamics. Refrigerated truck aerodynamics have remained unchanged or have regressed over the past few decades. The aerodynamics of refrigerated trucks could be improved along with inner air distribution. Reduction of the truck’s air resistance should not reduce the air exchanges in the condensing unit.
Colour: trucks, and especially the large surface area of their insulated bodies, are attractive for marketing and advertising purposes, but the colour and the type of external surface of the body can impact up to 40% on the energy consumption of the refrigeration unit. Communication should help users find the right design for their advertising.

Refrigerating equipment developments

The most common refrigeration system in use for refrigerated food transport applications today is the vapour-compression system powered by a diesel engine. The manner in which the refrigeration unit is run is the basis on which equipment in road vehicles is classified, as either "dependent" or "independent":

- independent (or self-contained, self-powered, diesel unit): equipped with an independent heat engine which runs the compressor, both on the road and during stops;
- dependent (or non-self-contained, vehicle powered): such equipment is generally dependent on the engine of the road vehicle. If the refrigeration compressor is driven directly by the vehicle’s engine, the refrigeration capacity can fall when the vehicle slows down (in the city) and ceases completely when the vehicle stops, and the engine is off, when it is advisable to plug the refrigeration unit into the local supply area if the unit is equipped with an electric motor. The link between vehicle engine speed and compressor speed can be modified by using up-to-date electric supply systems: vehicle engine → electric generator → static converter → electric (hermetic) compressor.

There is still room for improvement in vapour-compression systems, in the refrigerant used for instance, or the reduction of leakage, but research on alternative production systems (absorption, adsorption, etc.) is also necessary.

- Cryogenic systems: the recent rapid increase in the price of diesel fuel has generated renewed interest in cryogenic systems, particularly for urban distribution. The system is autonomous and cooled by cryogenic coolants. Such equipment uses liquid nitrogen or CO₂ as a cryogenic fluid that is sprinkled inside the insulated body or cools an evaporator in a semi-closed system, where evaporated gas is vented out of the refrigerated body. It is also less noisy and cools transported goods faster than conventional equipment. More than 1000 vehicles equipped with such systems are in service in Germany and France.

- Sorption systems: new innovative solutions such as ad- or absorption cycles are being tested. In heat-driven refrigeration technologies, absorption and/or adsorption, the conventional mechanical compressor of the common vapour-compression cycle is replaced by a “thermal compressor” and a sorbent. These systems, even if they generally offer lower COPs, can use waste energy, thus reducing the environmental impact of the technology.

- Hybrid systems: the transport refrigeration systems of the future could also be hybrid systems. The types of system in the hybrid arrangement will depend to a large extent on the size of the vehicle and the type of distribution. The increasing use of hybrid vehicles requires comparable or at least compatible refrigeration solutions.

- Phase-change materials (PCMs): refrigerant systems offer good temperature homogeneity and stability, even during delivery. Nevertheless, their market share has dropped considerably in recent decades. Energy storage with phase-change materials could certainly become increasingly important, particularly if the PCMs are charged using renewable energy. These materials, acting as heat reservoirs, could increase the efficiency of the refrigeration circuit because of their ability to store large amounts of energy and release or absorb it in the form of heat. The use of such a system could be valuable, especially when the system is not in operation (compressor turned off), but there is a requirement to cool a body down or to stabilize at a required temperature.

Refrigerant issues

For 30 years, refrigeration has greatly participated in the reduction of the overall Ozone Depletion Potential (ODP) in the world by banning CFCs and now HCFCs, including in the refrigerated transport field.

- F-gases: the vast majority of refrigerated vehicles use now HFCs as refrigerant, mainly R404A, R134a and R410A which have very high Global Warming Potentials (GWPs). The typical annual refrigerant leakage rate in refrigerated transport could be as high as 25%. 2% of the global consumption of HFCs is used in refrigerated vehicles. The impact of HFCs on the environment is still strong but, it can be lowered by developing new HFCs with low GWPs or by reducing the refrigerant charge in the refrigeration unit. HFCs such as R141b are still used as foam-blowing agents in vehicle insulation in some countries.

- Natural refrigerants: research and development should focus on the use of natural refrigerants, for instance the replacement of banned gases by CO₂, or in fewer instances by NH₃ or hydrocarbons such as R290 and R600a in traditional compression systems. Equipment using CO₂ as refrigerant is already being field tested for marine containers, but testing is still in the early stages in the road transport field.
Management and logistic aspects

- **Intermodal transport:** even if 80% of global transport of goods is carried out using marine containers on ships, about 44% of all goods in the EU are transported by road.\(^{10}\) Shippers prefer road transport because of its flexibility and the possibility of providing door-to-door service. However, this type of transport increases road congestion in urban areas. An optimal solution might be the combined use of all means of transport: road, rail, inland waterways, and short-distance shipping. Currently, intermodal freight service only accounts for only about 5-7% of the total tonnage transported.\(^{11}\)

- **Small individual containers and packaging:** small insulated containers have a capacity of a few litres to 2 m\(^3\) and operate using eutectic plates, dry ice, Peltier, compression or absorption systems, allowing for autonomy of up to 24 hours. These containers are useful logistic alternatives since they are flexible, make it very easy to transport very different types of goods (frozen or chilled) in the same vehicle and do not require controlled-temperature hubs for loading or unloading of trucks.

- Insulated or refrigerated packaging is increasingly used for the transport of pharmaceuticals and foodstuffs. These solutions, quite recent on the market, can be further improved in terms of insulation and useful capacity. Their development also allows new logistic systems for online business or specific distribution.\(^{12}\)

- **Road congestion:** some initiatives have been proposed to avoid road congestion:
  - **Transport sharing:** in 2008, 37 of the UK’s largest companies had signed up for the “Sustainable Distribution Initiative”. The objective consists in the removal of 800 trucks from UK roads per year, cutting energy use by about 23 million litres of diesel fuel.\(^{13}\)
  - **Night delivery:** an efficient solution to limit the environmental impact due to traffic jams, thereby reducing transport time, the number of trucks and energy consumption by up to 40%. Night delivery could be implemented on a large scale if quiet refrigerated vehicles are used and do not constitute an important source of disturbance for urban populations. Major efforts have been undertaken in order to reduce the noise generated by transport equipment, mainly refrigeration systems. The behaviour of the driver and the quality of reception devices also need to be improved to achieve silent night delivery.\(^{14}\)

- **Training of truck drivers:** refrigerated transport sustainability is also a staff challenge. Truck drivers can reduce fuel consumption by adopting “environmentally friendly driving methods”. During delivery operations, they should limit door openings which are major sources of thermal losses.

- **Dimensions of the bodies:** longer trailers and modular systems such as tandem trailers: in refrigerated transport, the average load, in particular in distribution, is very low, and can be under 10 t for a semi-trailer with a transport capacity of 26 t!\(^{15}\)
  - Modular systems such as tandem trailers (where 2 trailers are coupled together and pulled by one truck) make it possible to strongly reduce the environmental impact of transport on some major roads. This technique is utilized in the USA as well as in Australia and works well between cities as it reduces the number of trucks on the road. They are being tested in several European countries within the framework of EMS (European Modular System) discussions. At the distribution hub, the trailers would then be unloaded to enable the contents to be distributed within urban areas.
  - Longer trailers, particularly in Europe, as used already in certain countries, should enable a considerable reduction in the environmental impact of refrigerated transport. For instance, new trailer construction techniques make it possible to increase the length of the trailers used on the same roads from 16.5 to 17.8 m. This equipment will be more efficient.

Conclusion

In the years ahead, the cold chain will be increasingly necessary to preserve food and pharmaceuticals. Along with the growth of refrigerated transport, it will play a major role in the coming years in supplying food and protecting the 9 billion inhabitants expected on the planet in 2050.\(^{16}\) With increased urbanization and hence greater distances between production areas and highly populated areas, refrigerated transport will play a major role in the addressing of these requirements.

Energy savings of up to 50% can certainly be achieved in the field of refrigerated transport of chilled and frozen products. Many non-vapour-compression refrigeration technologies, e.g. adsorption, absorption, liquid-gas cryogenic systems, and eutectics, have been tested. The use of natural refrigerants to replace HFCs is being investigated. In addition, solutions for energy production, storage and transmission such as hydraulic, electric, indirect refrigeration, independent production or vehicle power use have been tested. Nevertheless, few new solutions have been implemented on the market, and there is a need to explore these solutions from environmental and energy efficiency standpoints. The number of solutions available on the market over the 10 next years will probably increase. Regulations and standards should be adapted to facilitate these innovations and increase their efficiency.
More than in the past, the addressing of the challenges introduced in this note will require coordination and extensive cooperation between the main stakeholders in this sector, above all manufacturers of insulated bodies, and also manufacturers of refrigeration unit. The interface with and the meeting of the needs of the final users are not to be neglected. To bring this successfully together, efficient, specialized scientific and technical support will be required.

Research focused on the achieving of greater efficiency with respect to the environment must also take into account the need to provide consumers with safe, wholesome foodstuffs, and temperature-sensitive pharmaceuticals, flowers and plants.

**Recommendations**

The IIR would like to highlight the following recommendations:
- Providing consumers with safe, wholesome foods and efficacious pharmaceutical products is a key priority;
- Sharing of best practices in order to achieve the highest possible hygiene and food safety standards should be improved;
- Improving the energy efficiency and the environmental performance of transport refrigeration systems, and the selection of refrigeration systems with no or a very slight impact on the climate, both in terms of energy use and greenhouse gas emissions, should be achieved;
- Developing new or previously neglected refrigerated logistic networks such as multimodal transport;
- The raising of public awareness regarding the long-term environmental and economic benefits of energy-efficient equipment should be a priority;
- Regulations and standards should facilitate innovations in refrigerated transport;
- Research and development in this sector should be supported to the greatest possible extent.

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**References**


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The International Institute of Refrigeration (IIR) is an intergovernmental organization comprising 60 Member Countries representing two thirds of the global population.

The IIR's mission is to promote knowledge and disseminate information on refrigeration technology and all its applications in order to address today's major issues, including food safety, protection of the environment and development of the least developed countries.

The IIR provides a wide range of services: organization of conferences, congresses, workshops and training courses, a database (Fridoc) containing 90 000 references, several publications (journals, manuals, technical books, conference proceedings, informatory notes), and a Web site providing a wide range of information: [www.iifiir.org](http://www.iifiir.org).