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Review

Safety Requirements for Transportation of Lithium Batteries

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Abstract: The demand for battery-powered products, ranging from consumer goods to electric vehicles, keeps increasing. As a result, batteries are manufactured and shipped globally, and the safe and reliable transport of batteries from production sites to suppliers and consumers, as well as for disposal, must be guaranteed at all times. This is especially true of lithium batteries, which have been identified as dangerous goods when they are transported. This paper reviews the international and key national (U.S., Europe, China, South Korea, and Japan) air, road, rail, and sea transportation requirements for lithium batteries. This review is needed because transportation regulations are not consistent across countries and national regulations are not consistent with international regulations. Comparisons are thus provided to enable proper and cost-effective transportation; to aid in the testing, packaging, marking, labelling, and documentation required for safe and reliable lithium cell/battery transport; and to help in developing national and internal policies.

Keywords: regulations; transport; safety; lithium-ion batteries; lithium-metal batteries

1. Introduction

When transporting goods by any mode (air, sea, train, truck), an item is considered hazardous if it is explosive, corrosive, flammable, toxic, or radioactive [1]. Batteries, and in particular, lithium batteries (the term "lithium batteries" includes the family of batteries having lithium-based chemistries and various types of cathodes and electrolytes.) present corrosive, flammable, toxic and explosive characteristics. In fact, the improper care of batteries in transportation, including preconditioning, packaging, and handling, has already resulted in fires, explosions, and the release of hazardous chemicals into the environment [2].

Batteries are classified into primary and secondary forms. A primary (non-rechargeable) cell or battery cannot be recharged and is discarded after the charge is spent. Common examples of their use are in watches, calculators, cameras, smoke detectors and defibrillators. A rechargeable battery is an energy storage device that can be recharged and reused. The most common rechargeable batteries are lead-acid, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and lithium-ion (Li-ion) batteries.

For the purposes of the regulations concerning dangerous goods, lithium batteries are categorized into lithium-metal (Li-metal) and Li-ion batteries. Li-metal batteries are typically non-rechargeable batteries that have Li-metal and lithium compounds as an anode and cathode, respectively. Li-ion

batteries represent a family of rechargeable batteries where the lithium is only available in ionic form in the electrolyte. Most conventional Li-ion cells use a carbon-based anode, with the positive electrode being a metal oxide that contains lithium such as $LiCoO_2$. Based on the product requirements, a battery may consist of 1 "battery" cell (e.g., smart phones) to more than 1000 cells (e.g., computers, power tools, electric vehicles). A cell is defined as a single encased electrochemical unit consisting of one positive and one negative electrode, which provides a voltage differential across these terminals. A battery is defined generally as two or more cells which are electrically connected together and having some forms of markings and protective devices, often including battery management software. Other terms include battery packs, battery modules and battery assemblies.

Due to their high energy-to-weight ratio, lithium batteries have become the preferred energy source for many products, from smart phones and computers to vehicles. However, lithium batteries present a safety risk since they can generate a great deal of heat if short circuited. Short circuits are possible if there are manufacturing defects or if the batteries have been improperly charged/discharged or used. If batteries are not designed, tested, manufactured, and prepared for transport in accordance with regulations, various hazardous conditions are possible [3,4].

Lithium batteries are classified under UN category 9 as dangerous goods because they are thermally and electrically unstable if they are subjected to certain uncontrolled environmental conditions or are mishandled during transportation. Battery hazards include electrolyte leakage, heat production, venting of gases, fire, and explosions. Battery product sheets also identify chemical hazards: liquid and gas leakage; electrical: short-circuit, high voltage, and failure of the battery management system; and mechanical: vibration, air pressure, shock, and deformation [5,6].

Once a lithium cell/battery ignites and catches fire, it can also propagate to nearby batteries, causing collateral overheating, fires, and explosions. These fires produce toxic fumes and are often difficult to put out with normal fire extinguishers. (The gas species of the toxic fumes are determined by a certain battery material. For a NMC/graphite (LiPF6 in EC:EMC) cell, 11 determinant gas mixture constituents were identified after a Li-ion battery caught fire, including EMC, DEC, EC, benzene, toluene, styrene, biphenyl, acrolein, CO, COS, and hydrogen fluoride [7].) The U.S. Federal Aviation Administration (FAA) studies related to the hazards produced by lithium cells show that aqueous extinguishing agents that contain water are the most effective at preventing thermal runaway propagation of Li-ion cells. Streamed non-aqueous agents are effective at extinguishing electrolyte fires, but ineffective at stopping propagation of thermal runaway from cell to cell [8].

Reports of battery fires and explosions are well known. For example, the FAA banned the Samsung Galaxy Note 7 from all flights since 14 October 2016 [9] due to numerous fires. In December 2015, the major U.S. airlines American, Alaska, Delta, Hawaiian, JetBlue, Southwest and United Airlines banned hoverboards on passenger flights and the U.S. Postal Service no longer ships hoverboards by air because of the possibility of fires [10,11]. Although e-cigarettes are not banned from shipping, from August 2009 to January 2017, 44 of the 214 reported e-cigarette explosions occurred during transport, storage and unknown circumstances [12].

Incidents involving lithium batteries catching fire on board aircraft include the UPS Air Cargo in Louisville, Kentucky on 7 June 2012; the FedEx Air Cargo in Pittsburgh, Pennsylvania on 15 September 2015; the FedEx Air Cargo in Memphis, Tennessee on 21 July 2016; and the Alaska Passenger in Ketchikan, Alaska on 30 October 2016 [13]. Most of these incidents allegedly occurred due to inappropriate packaging or handling that damaged the batteries and triggered an electrical short. However, the grounding of Boeing 787 Dreamliners in January 2013 was a result of operational Li-ion batteries, which served as a backup to the on-board power system. Whereas similar incidents can occur with other battery technologies such as lead, nickel, and alkaline, these chemistries do not pose such a major risk because they do not lead to thermal runaway or explosion. Because of the hazards associated with lithium batteries, transportation of lithium batteries is regulated in order to prevent accidents and damage [14–16].

International, national, and regional governments, as well as other authorities, have developed regulations for air, road, rail, and sea transportation of lithium batteries and the products that incorporate these batteries. The regulations govern conduct, actions, procedures, and arrangements. The regulations are meant to ensure that shippers transport lithium batteries and battery-powered products safely within their country or internationally. The national regulations and the norms (specific standards, models, and patterns) issued by the local government or companies are usually similar to those defined by the international standards for specific transportation modes, but there are differences in compliance [2].

This paper is organized as follows: Section 2 summarizes the testing standards for shipment of lithium batteries. Section 3 reviews the packing methods, hazard communication requirements (i.e., package marking, labelling, and accompanying documents), and handling methods provided in the international regulations for the safe transport of lithium batteries by various transport modes. Sections 4–8 introduce lithium battery transportation regulations in the U.S., China, Europe, South Korea, and Japan, and discuss the differences between the national and international regulations. Section 9 presents conclusions and recommendations for safe transportation of lithium batteries.

The main contributions of this paper include: (1) information on packaging, hazard communication requirements, and handling methods, for companies to better understand and comply with the international regulatory requirements for transporting lithium batteries; (2) information on the differences among U.S., Chinese, European, South Korean, and Japanese regulations for different kinds of lithium batteries and for various transport modes; (3) comparisons between U.S., Chinese, European, South Korean, and Japanese transport regulations, which will help in developing national and international policies and designing criteria for testing, packaging, marking, labelling, documentation, and handling of batteries for transport; and (4) recommendations for companies to ensure success in transporting batteries and in preparing for new regulations.

2. Safety Tests for Shipment of Lithium Batteries

Prior to being shipped to, from, or within any countries, lithium batteries must be certified by passing safety tests. The United Nations (UN) safety tests are widely considered the fundamental global transportation safety testing standards. Other than the UN tests, for some specific products, especially those which have installed batteries, such as cell phones and laptops, additional industry-specific standards must be passed as well. The purposes of these test standards are discussed in this section.

2.1. UN Safety Tests

The UN Manual of Tests and Criteria presents the UN schemes for classification of dangerous goods and describes the test methods and procedures for proper classification of referenced materials for transport. Considered one of the key transportation testing standards, the manual must be followed by manufacturers that ship lithium batteries. The manual was established according to the UN Recommendations on the Transport of Dangerous Goods-Model Regulations and the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) [17]. The UN safety test is a self-certified standard. However, because of potential liability issues, most manufacturers select a third-party certified test lab to conduct the tests.

For any mode of transport, every cell and battery (except for low-production-run or prototype lithium cells or batteries must pass the tests specified in the UN Manual of Tests and Criteria, Part III, Subsection 38.3, prior to their transport. (Low-production-run means annual production runs consisting of no more than 100 lithium cells or batteries [18].) If a cell or battery type does not meet the test requirements, it must be retested after the defects are corrected. Furthermore, test reports must be submitted to the Committee of Experts [19], and include the quantity or number of cells/batteries per package, and the type and construction of the packaging.

The specific test procedures for lithium cells and batteries are summarized in Table 1. In general, test procedures depend on whether the item is a cell or battery type. All cell types need to undergo Tests

T.1 to T.6 and T.8. All non-rechargeable battery types, including those composed of cells previously tested, must pass Tests T.1 to T.5. All rechargeable battery types, including those composed of previously tested cells, need to undergo Tests T.1 to T.5 and T.7. In addition, a single-cell rechargeable battery with overcharge protection needs to pass Test T.7. A cell as a component of a battery that is not transported separately from the battery only needs to be tested in accordance with Tests T.6 and T.8. A cell that is transported separately from the battery must pass Tests T.1 to T.6 and T.8 [19].

Table 1. UN tests T.1 to T.8 for lithium cells and batteries prior to being transported.

Test Step	Test Type	Specific Procedures
Test T.1	Altitude simulation	Test cells and batteries stored at a pressure of 11.6 kPa or less for at least 6 h at ambient temperature (20 ± 5 °C).
Test T.2	Thermal	Rapid thermal cycling between high (75 ± 2 °C) and low (−40 ± 2 °C) storage temperatures, stored for at least 6 h at the test temperature, time interval between high and low test temperature change less than 30 min.
Test T.3	Vibration	The vibration is a sinusoidal waveform with a logarithmic sweep between 7 Hz (1 g_n peak acceleration) and 200 Hz (8 g_n peak acceleration) and back to 7 Hz; 12 times cycle, 3 mutually perpendicular mounting positions.
Test T.4	Shock	Subjected to a half-sine shock (150 g_n peak acceleration) and pulse duration (6 ms); 3 shocks cycling in the positive and negative directions for each of 3 mutually perpendicular mounting positions (total of 18 shocks).
Test T.5	External short circuit	Short circuit with a total external resistance of less than 0.1 Ω at (55 ± 2 °C), 1 h duration.
Test T.6	Impact	A 15.8-mm-diameter bar placed across the sample cell center, and a 9.1-kg mass is dropped from a height of (61 ± 2.5 cm) onto the sample.
Test T.7	Overcharge	Overcharging test should be conducted for 24 h with charge current (twice the manufacturer's recommended maximum) and minimum test voltage. The minimum test voltage is defined in two categories (a) when recommended charge voltage ≤18 V and (b) when recommended charge voltage >18 V: Both categories are further explained as:
		(a) the lesser of 22 V or 2 times the maximum charge voltage or,
		(b) 1.2 times the maximum charge voltage.
Test T.8	Forced discharge	Each cell is forced discharged by connecting it in series with a 12 V DC power supply at an initial current equal to the maximum discharge current specified by the manufacturer.

Tests T.1 to T.5 are conducted in sequence on the same cell or battery. Test T.7 is conducted on undamaged batteries previously tested under tests T.1 to T.5 for purposes of testing on cycled batteries. Tests T.6 and T.8 are conducted on cells and batteries that have not undergone any other test steps.

2.2. Additional International Safety Tests for Lithium Batteries

In addition to the UN 38.3, several international organizations serving the transportation industry have developed international regulatory standards for specific industries/products that contain cells/batteries (see Table 2). Some of these standards, such as the International Electrotechnical Commission (IEC) standards, are widely referenced by different countries/districts to establish their own battery test standards. The impacts of these international standards on different countries will be introduced in the latter sections. This section briefly introduces the scope of these standards.

Table 2. Additional international standards [20,21].

Organization	Safety Standards
IEC	IEC 62133: Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes—Safety Requirements for Portable Sealed Secondary Cells, and for Batteries Made from Them, for Use in Portable Applications. IEC 62281: Safety of Primary and Secondary Lithium Cells and Batteries During Transport.
IEEE	IEEE 1625: Rechargeable Batteries for Multi-Cell Mobile Computing Devices. IEEE 1725: Rechargeable Batteries for Cellular Telephones.
SAE	SAE J 2929: Electric and Hybrid Vehicle Propulsion Battery System Safety Standard Lithium-Based Rechargeable Cells. SAE J 2464: Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System Safety and Abuse Testing.
UL	UL 1642: Lithium Batteries. UL 1973: Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications. UL 2054: Household and Commercial Batteries. UL 2580: Batteries for Use in Electric Vehicles. UL 2271: Batteries for Use in Light Electric Vehicle Applications. UL 2272: Electrical Systems for Self-Balancing Scooters.

The IEC, a non-profit standards organization, publishes international standards for all electric, electronic, and related technologies, including batteries. IEC 62133 has been key for shipping Li-ion batteries used in portable applications such as IT equipment, medical devices, power tools, and household applications, since 2002. In addition to UN 38.3, the cells that are used for portable applications must be certified to IEC 62133. When Europe and South Korea established their own standards for battery transport, for the most part they complied with the IEC standards, including IEC 62133 and IEC 622881.

The Institute of Electrical and Electronics Engineers (IEEE) has developed safety standards for lithium batteries. The key standards related to battery transport are contained in IEEE 1625 and IEEE 1725. IEEE 1625 covers multi-cell mobile computing devices, while IEEE 1725 covers cellular phones.

The Society of Automotive Engineers (SAE) has developed standards for electric vehicle (EV) batteries, including SAE J 2929 and J 2464, which cover propulsion battery system safety standard and energy storage system in the EV industry, respectively.

Underwriters Laboratories (UL) has also developed battery safety standards, which include more abusive tests, to cover different battery applications not covered by UN 38.3. Additionally, UL offers battery safety certification for battery shipping across different countries.

For emerging battery-powered products, such as self-balancing scooters (hoverboards), there have been no international standards until recently. The problem is that, while batteries can be certified individually, there have been no regulations to certify the overall product containing a battery. It was only after numerous fire incidents pertaining to the batteries of hoverboards, that UL issued a change to their safety certification (UL 2272) on 21 November 2016. The change provided the regulations so that self-balancing scooters, as well as other types of personal e-mobility devices can be certified, shipped and sold in the U.S. [22,23].

3. International Regulations for the Safe Transport of Lithium Batteries

The UN Model Regulations provide international guiding principles on all aspects of transporting dangerous goods, with inputs from a variety of organizations involved in designing and governing policies for safe and reliable transport across borders (see Figure 1). In addition, UN offices are spread over countries to help in developing the UN model, the International Air Transport Association Dangerous Goods Regulations (IATA DGR), the International Maritime Dangerous Goods (IMDG) Code, the European Agreement concerning International Carriage of Dangerous Goods by Road

(ADR), and the European Regulation concerning the International Carriage of Dangerous Goods by Rail (RID) [24].

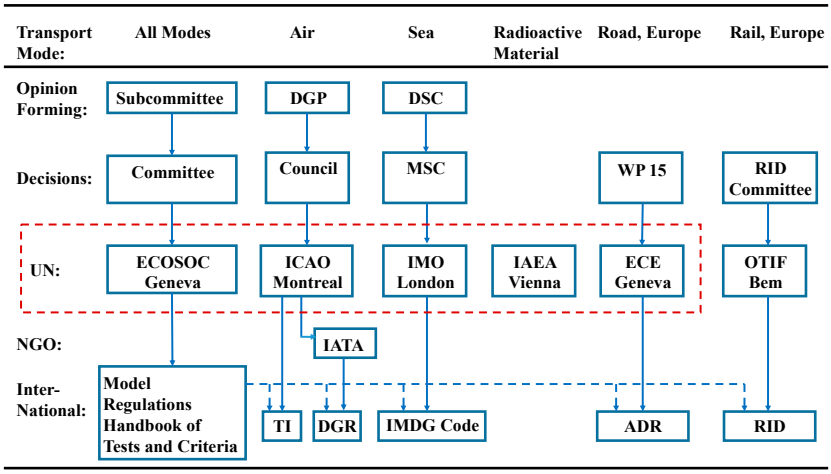

Figure 1. UN committees and councils for safe and reliable transport across borders.

The International Civil Aviation Organization (ICAO) has developed regulations for all international air shipments of hazardous materials. The International Air Transport Association (IATA) builds on the UN/ICAO rules and incorporates individual airline and governmental requirements into their Dangerous Goods Regulations (DGR) documents. The United Nations Economic Commission for Europe (UNECE) sponsors the ADR [25] to increase the safety of international transport of dangerous goods by road (including wastes by road). In addition, the Intergovernmental Organization for International Carriage by Rail (OTIF) develops the RID regulations [26], which apply to the international carriage of dangerous goods by rail. The International Maritime Organization (IMO) is the regulatory body for all shipments of dangerous goods on the high seas [27].

3.1. UN Model Regulations

UN Model Regulations were originally developed by the UN Economic and Social Council (ECOSOC)'s Committee of Experts on the Transport of Dangerous Goods "in the light of technical progress, the advent of new substances and materials, the exigencies of modern transport systems and, above all, the requirement to ensure the safety of people, property, and the environment" [28]. The secretariat of the UNECE has published the latest UN Model Regulations (19th revised edition) and provides secretariat services to the UN Economic and Social Council's Committee of Experts [29]. These regulations allow uniform development of national and international regulations ruling the different transport modes (e.g., air, road, rail, and sea) by presenting a basic scheme of provisions (see Figure 2 for multi-mode transportation based on the UN Model Regulations).

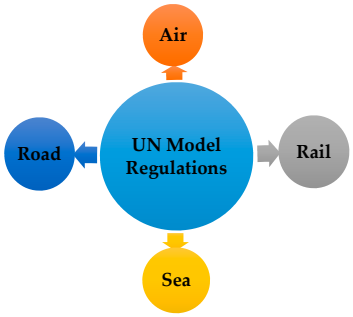

Figure 2. Multi-mode transportation based on the UN Model Regulations.

A four-digit UN number is assigned by the UN Committee of Experts on the Transport of Dangerous Goods and by the Globally Harmonized System of Classification and Labelling of Chemicals for identification of an article or substance or a particular group of articles or substances [30]. Per the Code of Federal Regulations, Title 49 (49 CFR) and the UN Model Regulations, Li-metal and Li-ion batteries are considered Class 9 hazardous materials (In 49 CFR and the UN Model Regulations, the numerical order of the classes does not correspond to the degree of danger).

Hazards associated with Li-metal and Li-ion cells may arise due to: flammable hydrogen gas; internal shorts caused by defects and dendrite formation; thermal runaway effects; and oxidation of organic solvents. For Li-ion batteries, hazards may originate from the side reactions including reactions between the organic solutions and the electrode surface, that is, the instability of the solid-electrolyte interface (SEI) with temperature increasing; and heat generation and thermal management [31]. In order to account for the different possible hazards associated with differential chemical and electrical content, the UN has separated different types of lithium batteries, as shown in Table 3.

Table 3. UN numbers and corresponding proper shipping names for lithium batteries.

UN Number	Proper Shipping Name
UN 3090	Li-metal batteries (including lithium alloy batteries).
UN 3091	Li-metal batteries contained in equipment [1] (including lithium alloy batteries).
UN 3091	Li-metal batteries packed with equipment (including lithium alloy batteries).
UN 3480	Li-ion batteries (including Li-ion polymer batteries).
UN 3481	Li-ion batteries contained in equipment [1] (including Li-ion polymer batteries).
UN 3481	Li-ion batteries packed with equipment (including Li-ion polymer batteries).

[1] Contained in equipment = equipment with cells or batteries properly installed; Packed with equipment = equipment + cells or batteries that are NOT installed in the equipment.

The UN Model Regulations are meant to cover all aspects of transportation necessary to provide international uniformity. They include a criteria-based classification system for substances that pose a significant hazard in transportation [32]. They set standards for packaging used to transport batteries. They also communicate the hazards of batteries in transport through hazard communication requirements, which include labelling and marking of packages, documentation, and emergency response information that is required to accompany each shipment.

In accordance with the UN Model Regulations, every lithium cell/battery has the same test requirements prior to transport, as discussed in Section 2. A safety venting device should be equipped for each battery, or each battery should be designed to prevent rupture under normal incident conditions during transport. External short circuits and reverse current flow should be prevented by adopting effective means for each battery. In addition, batteries should be manufactured under a quality management program. IATA DGR 3.9.2.6 includes the elements that must be included in such a program [18,29].

The UN Model Regulations present information for transport of several types of lithium batteries, including new and undamaged batteries, low-production-run or pre-production prototype batteries, disposable or recyclable lithium batteries, and damaged or defective lithium batteries. Based on the UN recommendations, regulations have been published for transporting lithium batteries using different transportation modes [33]. Transportation information about packing, maximum net quantity per package, maximum number of cells or batteries per package, marking, labelling, and documentation for lithium batteries are formally regulated according to their size (lithium content or watt-hour rating). Net quantity in the package means the weight or volume of the Li-ion batteries contained in a package excluding the weight or volume of any packaging material. For "Li-ion batteries contained in equipment", the net quantity is the net weight of the Li-ion batteries in the package [18].

3.2. International Regulations for Transportation by Air

Two international organizations regulate the international transport of dangerous goods by air: ICAO and IATA. IATA works with governments, the ICAO, and the member airlines to develop regulations that ensure safety and facilitate fast and efficient transport of dangerous goods by air [34]. Specific requirements for safe transportation of lithium batteries by air in both cargo and passenger aircrafts are determined by the ICAO, and these are then reflected in the IATA DGR [5]. The IATA DGR manual is based on the ICAO Technical Instructions (TI); it is the global reference for preparing, shipping, and transporting dangerous goods by air and the only standard recognized by the world's airlines.

According to the ICAO TI and the IATA DGR, lithium batteries can be transported by air if they meet the general requirements on cell or battery UN tests, ventilation, short-circuit prevention, reverse current flow prevention, and manufacture as discussed in Section 2.1. In addition, low-production-run or prototype lithium batteries may be transported aboard cargo aircraft if approved by the appropriate authority of the State of Origin. Waste lithium batteries and lithium batteries (including UN 3090 and UN 3480) being shipped for recycling or disposal are forbidden from air transport unless approved by the appropriate national authority of the State of Origin and the State of the Operator [35–37]. Furthermore, all kinds of Li-metal and Li-ion batteries (including UN 3090, UN 3091, UN 3480, and UN 3481) are forbidden from transport if they are identified by the manufacturer as being defective or damaged, because they can potentially produce a dangerous risk of heat, fire, or explosion.

Lithium batteries belong to IATA DGR Class 9, and specific shipping requirements for this type of cargo are different from those for other dangerous goods. Tables 4–7 summarize guidance information pertaining to limits on the number and net quantity per package, packaging, package marking, labelling, and documents for air transport based on the ICAO TI, the IATA DGR, and references [38–40]. The guidance information is meant to help transporters, including shippers, freight forwarders, ground handlers, airlines, and passengers, to comply with international requirements for transporting lithium batteries by air. Specifically, Tables 4 and 5 apply to air transportation of new, undamaged, small-size and non-small-size Li-metal batteries, and Tables 6 and 7 apply to new, undamaged, small-size and non-small-size Li-ion batteries. For Li-metal cells or batteries, small size refers to the lithium content in a cell is less than 1.0 g and that in a battery is less than 2.0 g; for Li-ion cells or batteries, small size refers to the watt-hour rating in a cell is less than 20 Wh and that in a battery is less than 100 Wh.

For standalone Li-ion batteries, UN 3480 packaging instruction 965 (PI965), effective from 1 April 2016, requires that the state of charge (SOC) of these batteries must not exceed 30% of their rated design capacity when they are transported. At the same time, these batteries are forbidden from transport on passenger aircraft. Furthermore, only one package prepared according to Section II of PI965 or PI968 is permitted per consignment for transport (consignment means one or more packages of dangerous goods accepted by an operator (airline) from one shipper at one time and at one address, receipted for in one lot and moving to one consignee at one address [18]). This package must also be separated from other cargo and should not be loaded into a unit load device (ULD) prior to being offered to the operator. IATA member airlines have to follow and enforce these regulations more severely than other airlines.

As shown in Tables 4–7, specific handling labels are required for lithium battery transportation according to Section II of PI965, PI966, PI967, PI968, PI969, and PI970. In addition, lithium batteries carried under Section IB of PI965 and PI968 also require the "caution" label besides the "Class 9" and the "Cargo Aircraft Only" labels.

Table 4. Guidelines for international air transportation of new, undamaged, small-size Li-metal batteries.

Packing Instructions	UN 3090-PI968				UN 3091-PI969	UN 3091-PI970	
	PI968-Section II			PI968-Section IB	PI969-Section II	PI970-Section II	
Description	Standalone Li-metal cells/batteries				Li-metal cells/batteries packed with equipment	Li-metal cells/batteries contained in equipment	
Aggregate lithium content (W)	$W_{cel} \leq 0.3$ g or $W_{bat} \leq 0.3$ g	$W_{cel} > 0.3$ g and $W_{cel} \leq 1$g	$W_{bat} > 0.3$ g and $W_{bat} \leq 2$ g	$W_{cel} \leq 1$ g or $W_{bat} \leq 2$ g	$W_{cel} \leq 1$ g or $W_{bat} \leq 2$ g	$W_{cel} \leq 1$ g or $W_{bat} \leq 2$ g	
Number (N) of cells or batteries per package	No limit	$N_{cel} \leq 8$	$N_{bat} \leq 2$	$N_{bat} > 2$ or $N_{cel} > 8$	Those necessary to power the equipment and 2 spares	$N_{bat} \leq 2$ or $N_{cel} \leq 4$	$N_{bat} > 2$ or $N_{cel} > 4$
Maximum net quantity per package	CAO: 2.5 kg; PAX: Forbidden	CAO: N/A; PAX: Forbidden	CAO: N/A; PAX: Forbidden	CAO: 2.5 kg; PAX: Forbidden	CAO: 5 kg PAX: 5 kg	CAO: 5 kg PAX: 5 kg	CAO: 5 kg PAX: 5 kg
Packing	First, Li-metal cells and batteries must be placed in inner packaging that completely encloses the cell or battery, cells and batteries must be protected against short circuits (only for batteries or batteries packed with equipment); Second, equipment must be secured against movement within the outer packaging and packed to prevent accidental activation; Third, strong outer packaging (e.g., cardboard box) required.						
Labelling						No	
Transport document	General warning statement (see Note 3)			"Shipper's Declaration for Dangerous Goods"	General warning statement	No	General warning statement
Description of content placed on the air waybill	"Li-metal batteries, in compliance with Section II of PI968-CAO"			UN 3090; Li-metal batteries, PI968 IB; Number of packages and gross mass per package	"Li-metal batteries, in compliance with Section II of PI969"	No	"Li-metal batteries, in compliance with Section II of PI970"
Number of packages per consignment or overpack	One			No limit	No limit	No limit	No limit

Note 1: W_{cel} denotes the weight of lithium per cell; W_{bat} denotes the weight of lithium per battery; Note 2: CAO: Cargo Aircraft Only; PAX: passenger aircraft; PI: packing instruction; N/A: not applicable. Note 3: The package contains Li-metal cells or batteries; the package must be handled with care and a flammability hazard exists if the package is damaged; special procedures must be followed in the event the package is damaged, to include inspection and repacking if necessary; and a telephone number for additional information.

Table 5. Guidelines for international air transportation of new, undamaged, non-small-size Li-metal batteries.

Description	UN 3090-PI968	UN 3091-PI969	UN 3091-PI970
	Standalone Li-Metal Cells/Batteries	**Li-Metal Cells/Batteries Packed with Equipment**	**Li-Metal Cells/Batteries Contained in Equipment**
Packing instructions	PI968-Section IA	PI969-Section I	PI970-Section I
Aggregate lithium content (W)	W_{cel} > 1 g or W_{bat} > 2 g		
Number of cells or batteries per package	No limit	Those necessary to power the equipment and 2 spares	No limit
Maximum net quantity per package	CAO: 35 kg PAX: Forbidden	CAO: 35 kg PAX: 5 kg	CAO: 35 kg PAX: 5 kg
Packing	First, Li-metal cells and batteries must be placed in inner packaging that completely enclose the cell or battery, cells and batteries must be protected against short circuits (only for batteries or batteries packed with equipment); Second, equipment must be secured against movement within the outer packaging and packed to prevent accidental activation; Third, UN approved packaging: Packing Group (PG) II.		First, equipment must be secured against movement within the outer packaging and packed to prevent accidental activation; Second, strong outer packaging (e.g., cardboard box) required; Third, UN approved packaging not required.
Labelling			
Transport document	Shipper's Declaration for Dangerous Goods: UN 3090 LI-METAL BATTERIES, 9, II	Shipper's Declaration for Dangerous Goods: UN 3091 LI-METAL BATTERIES PACKED WITH EQUIPMENT, 9, II	Shipper's Declaration for Dangerous Goods: UN 3091 LI-METAL BATTERIES CONTAINED IN EQUIPMENT, 9

Note 1: W_{cel} denotes the weight of lithium per cell; W_{bat} denotes the weight of lithium per battery; Note 2: CAO: Cargo Aircraft Only; PAX: passenger aircraft; PI: packing instruction; N/A: not applicable. Note 3: The package contains Li-metal cells or batteries; the package must be handled with care and a flammability hazard exists if the package is damaged; special procedures must be followed in the event the package is damaged, to include inspection and repacking if necessary; and a telephone number for additional information.

Table 6. Guidelines for international air transportation of new, undamaged, small-size Li-ion batteries.

Packing Instructions	UN 3480-PI965				UN 3481-PI966	UN 3481-PI967	
	PI965-Section II			PI965-Section IB	PI966-Section II	PI967-Section II	
Description	Standalone Li-ion cells/batteries (SOC $\leq$ 30%)				Li-ion cells/batteries packed with equipment	Li-ion cells/batteries contained in equipment	
Li-ion cells/batteries Watt-hour (E) rating	$E_{cel} \leq 2.7$ Wh	E_{cel} >2.7 Wh and $E_{cel} \leq 20$ Wh	E_{bat} > 2.7 Wh and $E_{bat} \leq 100$ Wh	$E_{cel} \leq 20$ Wh or $E_{bat} \leq 100$ Wh	$E_{cel} \leq 20$ Wh or $E_{bat} \leq 100$ Wh	$E_{cel} \leq 20$ Wh or $E_{bat} \leq 100$ Wh	
Number (N) of cells or batteries per package	No limit	$N_{cel} \leq 8$	$N_{bat} \leq 8$	$N_{bat} > 2$ or $N_{cel} > 8$	Those necessary to power the equipment and 2 spares	$N_{bat} \leq 2$ or $N_{cel} \leq 4$	$N_{bat} > 2$ or $N_{cel} > 4$
Maximum net quantity per package	CAO: 2.5 kg; PAX: Forbidden	CAO: N/A; PAX: Forbidden	CAO: N/A; PAX: Forbidden	CAO: 10 kg; PAX: Forbidden	CAO: 5 kg PAX: 5 kg	CAO: 5 kg PAX: 5 kg	CAO: 5 kg PAX: 5 kg
Packaging	First, Li-ion cells and batteries must be placed in inner packaging that completely encloses the cell or battery, cells and batteries must be protected against short circuits (only for batteries or batteries packed with equipment); Second, equipment must be secured against movement within the outer packaging and packed to prevent accidental activation; Third, Strong outer packaging (e.g., cardboard box) required.						
Labelling						Not Require	
Transport document	General warning statement (see Note 3)			"Shipper's Declaration for Dangerous Goods"	General warning statement	No limit	General warning statement
Information on the air waybill	"Li-ion batteries, in compliance with Section II of PI965-CAO"			UN 3480; Li-ion batteries, PI965 IB; Number of packages and gross mass per package	"Li-ion batteries, in compliance with Section II of PI966"	Not Require	"Li-ion, batteries in compliance with Section II of PI967"
Number of packages per consignment or overpack	One			No limit	No limit	No limit	No limit

Note 1: E_{cel} denotes the watt-hour per cell; E_{bat} denotes the watt-hour per battery; Note 2: CAO: Cargo Aircraft Only; PAX: passenger aircraft; PI: packing instruction; N/A: not applicable; Note 3: The package contains Li-ion cells or batteries; the package must be handled with care and a flammability hazard exists if the package is damaged; special procedures must be followed in the event the package is damaged, to include inspection and repacking if necessary; and a telephone number for additional information.

Table 7. Guidelines for international air transportation of new, undamaged, non-small-size Li-ion batteries.

Description	UN 3480-PI965	UN 3481-PI966	UN 3481-PI967
	Standalone Li-Ion Cells/Batteries (SOC $\leq$ 30%)	**Li-Ion Cells/Batteries Packed with Equipment**	**Li-Ion Cells/Batteries Contained in Equipment**
Packing instructions	PI965-Section IA	PI966-Section I	PI967-Section I
Li-ion cells/batteries Watt-hour rating (E)	E_{cell} > 20 Wh or E_{bat} > 100 Wh		
Maximum net quantity per package	CAO: 35 kg PAX: Forbidden	CAO: 35 kg PAX: 5 kg	CAO: 35 kg PAX: 5 kg
Number of cells or batteries per package	No limit	Those necessary to power the equipment and 2 spares	No limit
Packaging	First, Li-ion cells and batteries must be placed in inner packaging that completely enclose the cell or battery, cells and batteries must be protected against short circuits (only for batteries or batteries packed with equipment); Second, equipment must be secured against movement within the outer packaging and packed to prevent accidental activation; Third, UN approved packaging: PG II.		First, equipment must be secured against movement within the outer packaging and packed to prevent accidental activation; Second, strong outer packaging (e.g., cardboard box); Third, UN approved packaging not required.
Labelling			
Transport document	Shipper's Declaration for Dangerous Goods: UN 3480 LI-ION BATTERIES, 9, II	Shipper's Declaration for Dangerous Goods: UN 3481 LI-ION BATTERIES PACKED WITH EQUIPMENT, 9, II	Shipper's Declaration for Dangerous Goods: UN 3481 LI-ION BATTERIES CONTAINED IN EQUIPMENT, 9
Information on the air waybill	"Dangerous Goods as per Shipper's Declaration"		

Note 1: E_{cel} denotes the watt-hour per cell; E_{bat} denotes the watt-hour per battery; Note 2: CAO: Cargo Aircraft Only; PAX: passenger aircraft; PI: packing instruction; N/A: not applicable; Note 3: The package contains Li-ion cells or batteries; the package must be handled with care and a flammability hazard exists if the package is damaged; special procedures must be followed in the event the package is damaged, to include inspection and repacking if necessary; and a telephone number for additional information.

Figure 3 shows the lithium battery handling Label (3a), the Cargo Aircraft Only Label (3b), and the Class 9 hazard Label (3c). Moreover, in 2016, both IATA and ICAO have issued that Li-ion cells and batteries (UN 3480-PI965 as shown in Tables 6 and 7) must be offered for transport at a SOC not exceeding 30% of their rated design capacity. Cells and/or batteries at a SOC of greater than 30% may only be shipped with the approval of the State of Origin and the State of the Operator under the written conditions established by those authorities [39,40].

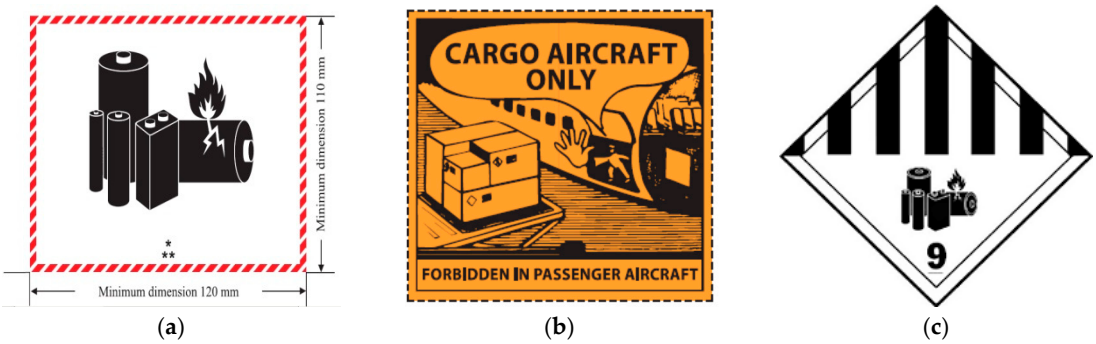

Figure 3. (**a**) Lithium battery handling label (* Place for UN numbers, ** Place for telephone number for additional information); (**b**) Cargo Aircraft Only label; (**c**) Class 9 hazard label.

3.3. International Regulations for Transport by Surface (Road/Rail/Sea Freight)

International regulations for the transport of lithium batteries by road, rail, and sea are summarized in this section. The UNECE Inland Transport Committee (ITC) facilitates the international movement of persons and goods by inland transport modes. The ADR sponsored by UNECE is intended to increase the safety of international transport of dangerous goods (including wastes) by road. The RID applies to the international transport of dangerous goods by rail. In addition, the International Maritime Dangerous Goods (IMDG) Code [41,42] is the international guideline for the safe shipment of dangerous goods by sea. It contains information on terminology, packaging, labelling, markings, stowage, segregation, handling, and emergency response and is intended for use not only by mariners but also by all those involved in industries and services connected with shipping.

According to the ADR, RID, and IMDG Code, lithium batteries (including UN 3090, UN 3091, UN 3480, and UN 3481) can be transported if they meet the provisions pertaining to the UN tests, ventilation, short-circuit prevention, reverse current flow prevention, and manufacture as noted in Section 3.1. In general, low-production-run or prototype lithium cells and batteries can be carried for testing if each battery can be individually packed in an inner packaging and placed in a suitable outer packaging, which meets the UN packaging criteria for packing group (PG) I. Dangerous goods are assigned to 3 different packing groups according to the degree of danger they present—PG I indicates the greatest danger; PG II indicates medium danger; and PG III indicates low danger. In the IATA DGR, PG II is assigned to Li-metal batteries (UN 3090-PI968, UN 3091-PI969 and UN3091-PI970 as shown in Tables 4 and 5) and Li-ion batteries (UN 3480-PI965, UN 3491-PI966 and UN 3481-PI967 as shown in Tables 6 and 7). In addition, when lithium batteries are carried for disposal or recycling, they must be designed or packed to prevent short circuits and the dangerous risk of heat. At the same time, they must be secured against excessive movement within the outer packaging, which must conform to the PG II performance level. Furthermore, packages for these batteries must be marked "LITHIUM BATTERIES FOR DISPOSAL" or "LITHIUM BATTERIES FOR RECYCLING".

Damaged or defective batteries may lead to short-circuiting or may catch fire through release of stored energy or hazardous contents. Proper packaging is one of the most critical measures that a shipper can consider to improve safety and prevent incidents. Before damaged or defective lithium batteries are transported, their outer packaging must conform to the approved PG I level. PG I must also be assigned to the low-prototype-runs. Batteries should be secured within the outer packaging

against excessive movement, and metal packaging should be fitted with a non-conductive lining material. In addition, batteries that are prone to rapidly disassemble, dangerously react, produce a flame or a dangerous evolution of heat or a dangerous emission of toxic, corrosive, or flammable gases or vapors under normal conditions of carriage should not be carried except under conditions specified by the competent authority [24,25,41,42].

From the ADR and the RID, lithium batteries belong to Class 9 articles and their classification code is M4, which means one category of subdivided substances and articles of Class 9. In addition, the passage of a road transport unit carrying lithium batteries is forbidden in category E road tunnels, which are assigned by the competent authority and indicated by a sign with an additional panel bearing a letter E. In accordance with the RID, lithium batteries are permitted for carriage as "express parcels," however, these parcels should not weigh more than 40 kg. Furthermore, the passage of a sea transport unit carrying lithium batteries is forbidden through category E tunnels if the gross mass of packages is less than 8 tons per transport unit marked in the IMDG Code. Tables 8 and 9 provide detailed information about packaging, hazard communication, and transport documents for international surface transportation of lithium batteries from the ADR, the RID, and the IMDG Code [38,43]. Table 8 discusses small-size batteries, and Table 9 discusses non-small-size batteries.

The details of packing containers and ADR-2015 general provisions are summarized in Table 10. ADR-2015 package instruction group II and special provisions instructions are more or less similar in IATA, ICAO, and IMDG instructions. Most of the common features of packaging requirements are: (a) cells/batteries shall be protected against short circuit and the dangerous evolution of heat and (b) cells and batteries shall be secured within the outer packaging to prevent excessive movement during carriage. ADR packaging instructions cover healthy, damaged, or defective cells and batteries under P903 and P908. ADR also provides packaging guidelines under P909 for recycling and disposal of cells/batteries. LP903 and LP904 are special packaging instructions for large consignment [40,44–48].

In addition, other SPs for packaging are given in the ADR that make exceptional cases for lithium cells and batteries with smaller size and capacity, underproduction, and damaged conditions and if the battery is equipped in powered vehicles. A list of such provisions is given in Table 11. These SPs are categories with UN numbers, for example, for UN 3090 and UN 3091, the SPs are 188, 230, 376, 377, and 636; for UN 3480, the SPs are 188, 230, 310, 348, 376, 377, and 636, and for UN 3481, the SPs are 188, 230, 348, 360, 376, 377, and 636. SP 188 defines the exemption from ADR SPs according to the Wh capacity and weight of the battery [49].

Table 8. Guidelines for international surface transportation of new, undamaged, small-size lithium batteries.

Description	Standalone Lithium Cells/Batteries	Lithium Cells/Batteries Packed with Equipment	Lithium Cells/Batteries Contained in Equipment	
Packing instructions	ADR/RID/IMDG Special Provision (SP)188	ADR/RID/IMDG SP188	ADR/RID/IMDG SP188	
Lithium content (W) or watt-hour rating (E)	Li-metal cells/batteries: $W_{cel} \leq 1$ g; $W_{bat} \leq 2$ g Li-ion cells/batteries: $E_{cel} \leq 20$ Wh; $E_{bat} \leq 100$ Wh			
Number of cells or batteries per package	No limit	No limit	$N_{bat} > 2$ or $N_{cel} > 4$	$N_{bat} \leq 2$ or $N_{cel} \leq 4$
Mass limit	30 kg gross mass of the package	No limit	No limit	No limit
Packaging	First, cells and batteries must be protected against short circuits and damage; Second, cells and batteries must be completely enclosed in inner packaging inside strong outer packaging (only for batteries or batteries packed with equipment); Third, equipment must be protected against accidental activation and packed in applicable strong outer packaging (only for batteries contained in equipment).			
Marking or labelling	First, shipment contains "Li-metal" or "Li-ion" batteries; Second, transport according to SP188; Third, the package shall be handled with care and in case of damage a flammability risk exists; Fourth, if the package is damaged, special procedures including inspection and repacking must be followed. Fourth, for more information, please call *** (phone number).			No limit
Sea freight container-marking	No requirement			
Transport document	General warning statement (document should list the same information as the above marking content)			No limit

Note 1: E_{cel} denotes the watt-hour per cell; E_{bat} denotes the watt-hour per battery; Note 2: W_{cel} denotes the weight of lithium per cell; W_{bat} denotes the weight of lithium per battery.

Table 9. Guidelines for international surface transportation of new, undamaged, non-small-size lithium batteries.

Description	Lithium Cells/Batteries	Lithium Cells/Batteries Packed with Equipment	Lithium Cells/Batteries Contained in Equipment
Packing instructions	ADR/RID/IMDG P903	ADR/RID/IMDG P903	ADR/RID/IMDG P903
Lithium content (W) or watt-hour rating (E)	Li-metal cells/batteries: $W_{cel} > 1$ g; $W_{bat} > 2$ g Li-ion cells/batteries: $E_{cel} > 20$ Wh; $E_{bat} > 100$ Wh		
Mass limit	ADR/RID: maximum 333 kg gross mass per transport unit.		
Packaging	First, cells or batteries must be packed and protected against damage and short circuits; Second, cells or batteries must be completely enclosed in inner packaging and packed with equipment, which must be secured against movement within the outer packaging; Third, applicable strong outer packaging is constructed for cells or batteries contained in equipment to prevent accidental operation; Fourth, UN approved packaging: PG II.		
Labelling			
Sea freight container-marking	 Container-Placards		
Transport document	ADR/RID: UN 3090/UN 3480, LI-METAL BATTERIES/LI-ION BATTERIES, 9, PG II, (E). Transport category 2. Sea freight (IMDG): IMO-DANGEROUS GOODS DECLARATION.	ADR/RID: UN 3091/UN 3481, LI-METAL/LI-ION BATTERIES PACKED WITH EQUIPMENT, 9, PG II, (E). Transport category 2. Sea freight (IMDG): IMO-DANGEROUS GOODS DECLARATION.	ADR/RID: UN 3091/UN 3481, LI-METAL/LI-ION BATTERIES CONTAINED IN EQUIPMENT, 9, (E). Transport category 2. Sea freight (IMDG): IMO-DANGEROUS GOODS DECLARATION.

Table 10. Packaging instructions per ADR-2015.

Packaging Instruction	Description
Instructions applied for all packaging	The following packaging is allowed under ADR general provisions 4.1.1 and 4.1.3: First, Drums (1A2, 1B2, 1N2, 1H2, 1D, 1G) Second, Boxes (4A, 4B, 4N, 4C1, 4C2, 4D, 4F, 4G, 4H1, 4H2) Third, Jerricans (3A2, 3B2, 3H2)
P903 for healthy cells and batteries	It applies if general provisions 4.1.1 and 4.1.3 are met. Cells or batteries shall be packed in packaging so that the cells or batteries are protected against damage that may be caused by the movement or placement of the cells or batteries within the packaging.
P908 for damaged or defective cells and batteries	First, each cell or battery shall be individually packed in inner packaging and placed inside an outer packaging, both packagings being leak-proof; Second, inner packaging shall be non-combustible, non-conductive, and thermally insulated; Third, sealed packaging shall have venting devices; Fourth, vibration, shock, and moving of cells must be prevented; Fifth, sufficient inert absorbent material shall be added to inner or outer packaging; Sixth, a cell or battery with a net mass > 30 kg shall be limited to one piece per outer packaging.
P909 for cells and batteries for disposal or recycling	First, metal packaging shall be fitted with a non-conductive lining material. Second, cells < 20 Wh (1 g Li) or batteries < 100 Wh (2 g Li) may be packed in strong outer packaging up to 30 kg; Third, if cells or batteries are contained in equipment, strong outer packaging may be used.
LP903, LP904	For large packages

Table 11. Special provisions for packaging instruction.

Special Provision	Description
188	Cells and batteries are not subject to other provisions of ADR if they meet the following criteria: First, cell rating is < 20 Wh or < 1 g lithium Second, battery rating is < 100 Wh or < 2 g lithium
230	Cells and batteries must meet provision of 2.2.9.1.7, which describes cell and batteries contained in equipment. The provision specifies pre-tests, cell configurations, and ventilation. QMP etc.
310	Tests of UN Manual Section 38.3 do not apply to production series of no more than 100 cells and batteries when these prototypes are carried for testing, if they are packed in an outer package meeting the criteria of packaging group I. Each cell and battery is individually packed in an inner packaging with cushioning material, which should be non-combustible and non-conductive.
348	Batteries manufactured after 31 December 2011 should be marked with the Wh rating on the outside case.
360	Vehicles only powered by Li-metal or Li-ion batteries should be classified under the entry UN 3171 battery-powered vehicle.
376	Damaged or defective cells or batteries not confirming the UN Manual of Tests and Criteria should comply with the requirements of this special provision: First, cells or batteries identified as being defective for safety reasons, cells or batteries that have leaked or vented, cells or batteries that cannot be diagnosed prior to carriage, and cells or batteries that have sustained physical or mechanical damage. Second, packages should be marked "DAMAGED/DEFECTIVE LI-ION BATTERIES" or "DAMAGED/DEFECTIVE LITHIUM-METAL BATTERIES", as applicable. Cells and batteries should be packed in accordance with packing instructions P908 or LP904, as applicable. Third, cells and batteries expected to react dangerously under the normal conditions of carriage should not be carried except under conditions specified by the competent authority.
377	First, cells and batteries for disposal or recycling may be packaged in accordance with P909. These cells and batteries are not subject to the requirements of 2.2.9.1.7 (a) to (e); Second, packages should be marked "LITHIUM BATTERIES FOR DISPOSAL" or "LITHIUM BATTERIES FOR RECYCLING".
636	Cells contained in equipment, during carriage, should not fall below 2 V or two-thirds of the voltage of the undischarged cell, whichever is the lower. Cells and batteries are not subject to the other provisions of ADR (including 376 and 2.2.9.1.7) if they meet the following conditions: First, P909 is completely applied except for the "additional requirements" of 1 and 2 where both and 1 specifies that cell and battery should be designed and packed to present short circuit and dangerous evolution of heat and 2 specifies the level of protections required for cell and battery; Second, the total amount of lithium cells or batteries per transport unit does not exceed 333 kg; Third, packages are marked "LITHIUM BATTERIES FOR DISPOSAL" or "LITHIUM BATTERIES FOR RECYCLING" as appropriate.

4. Lithium Battery Transportation in the United States

In addition to complying with the international regulations discussed in Section 3, different countries generally have their own regional requirements for transportation of lithium batteries. In general, if the U.S. transportation regulations regulate a material, but the international regulations do not, the material must be transported according to the requirements of the U.S. transportation regulations [50].

4.1. Transportation Regulations Available in the United States

Part 49 of the Code of Federal Regulations (49 CFR Sections 100–185), of the U.S. Hazardous Materials Regulations (HMR) governs the domestic transportation of lithium batteries to, from, and within the U.S. by all modes, i.e., air, road, rail, and sea. It provides information on packaging, hazard communication (e.g., package marking, labelling, and shipping papers), and handling of batteries and battery-powered devices.

The 49 CFR is based on the UN Model Regulations and is in accordance with the international regulations including the ICAO TI and the IMDG Code. However, 49 CFR is not consistent in all respects with international regulations. Compliance with 49 CFR will not guarantee acceptance by regulatory bodies outside the U.S. [51]. Therefore, outside the U.S. (for transport to and from the U.S.), the UN Model Regulations for transporting batteries should be followed. In addition, the other international regulations introduced in Section 2.2 will guide lithium battery transportation by different transport modes internationally.

4.2. Differences between U.S. and International Regulations

Prior to being transported to, from, and within the U.S., lithium batteries must meet the general requirements in 49 CFR and the above-mentioned international transport regulations. As stated in Section 4.1, there are some differences between 49 CFR and the international regulations. In the U.S., each manufacturer must create and make available a record of satisfactory completion of the UN testing prior to offering lithium batteries for shipping. This record must be maintained as long as the design is offered for transportation, and after that it should be sequentially kept for one year [52]. Under 49 CFR, lithium batteries must be placed in non-metallic inner packaging that completely encloses them. Furthermore, 49 CFR provides a medium-size lithium battery category, whereas the international regulations do not. According to 49 CFR, medium-size lithium cells and batteries can only be transported by ground (i.e., by road and rail). Their outer package must be marked "LITHIUM BATTERIES—FORBIDDEN FOR TRANSPORT ABOARD AIRCRAFT AND VESSEL". Moreover, there are some additional requirements in the U.S. for the use of the IMDG Code. Lithium batteries can be transported to, from, or within the U.S. by sea, motor carrier, and rail according to the IMDG Code if all or part of the transportation is by sea. When lithium batteries are transported in accordance with the IMDG Code, for small-size standalone Li-metal batteries transported in accordance with SP 188, each of the outer packages must be marked "PRIMARY LITHIUM BATTERIES—FORBIDDEN FOR TRANSPORT ABOARD PASSENGER AIRCRAFT" or "LITHIUM-METAL BATTERIES-FORBIDDEN FOR TRANSPORT ABOARD PASSENGER AIRCRAFT", or labelled with the "Cargo Aircraft Only" label [53]. The U.S. transport regulations for shipping lithium batteries are also based on the size of the battery to be shipped [2]. Table 12 outlines the size categories covered by 49 CFR in the U.S.

Table 12. Size categories of Li-metal and Li-ion batteries for 49 CFR.

Size	Li-Metal		Li-Ion		Shipping Classification	Special Packaging/Markings Required
	Cell	Battery	Cell	Battery		
Small (no more than)	1 g	2 g	20 Wh	100 Wh	Excepted	Yes
Medium (between)	1 g and 5 g	2 g and 25 g	20 Wh and 60 Wh	100 Wh and 300 Wh	Class 9 (except by motor vehicles or rail) [54]	Yes
Large (more than)	5 g	25 g	60 Wh	300 Wh	Class 9	Yes

49 CFR is consistent with the international regulations for transport of low-production-run or prototype lithium batteries and lithium batteries for disposal or recycling. Specifically, low-production-run or prototype lithium batteries must be approved by the Associate Administrator prior to transportation aboard aircraft [55]. Disposable and recyclable lithium batteries, when packed in a strong outer packaging and carried by motor vehicles, are exempted from the UN testing, record-keeping, and specific packaging requirements. Damaged or defective lithium batteries can be transported by surface only, which follows the same restriction by the international regulations. However, there are some differences for transportation of damaged or defective lithium batteries in the U.S.—a comparison is given in Table 13.

Table 13. Comparison of international vs. U.S. regulations for shipping damaged or defective lithium batteries.

Regulation Category	International Regulations		U.S. HMR (49 CFR)
Available Transport Modes	**Road/Rail/Sea**		**Road/Rail/Sea**
Number of cells or batteries per package	No limit (if net mass per cell or battery $\leq$ 30 kg)	Only one (if net mass per cell or battery > 30 kg)	No limit
Packaging	First, each cell or battery must be individually packed in inner packaging (which is surrounded by thermal insulation material) inside an approved outer packaging; Second, metal packaging should be fitted with a non-conductive lining material; Third, UN approved packaging: PG II.		First, each cell or battery must be placed in individual, non-metallic inner packaging (which is surrounded by cushioning material) inside an approved outer packaging; Second, UN approved packaging: PG I.
Marking	"DAMAGED/DEFECTIVE LITHIUM-METAL BATTERIES" or "DAMAGED/DEFECTIVE LI-ION BATTERIES"		"DAMAGED/DEFECTIVE LITHIUM-METAL BATTERIES" or "DAMAGED/DEFECTIVE LI-ION BATTERIES"

Table 13 shows that the international regulations and 49 CFR follow similar regulations for the same transport modes and marking methods for transporting damaged or defective lithium batteries. However, the allowed number of cells/batteries per package differs. The international regulations allow only one battery per outer package if its net mass exceeds 30 kg. 49 CFR uses PG I packaging level for damaged or defective lithium batteries, whereas international regulations recommend PG II.

The ICAO and IATA have imposed new restrictions on lithium batteries shipped by air starting 1 April 2016. These restrictions include: (1) a 30% SOC limit on all air shipments of standalone Li-ion batteries; (2) a prohibition on transporting standalone Li-ion batteries as cargo aboard passenger aircraft; and (3) a limit of no more than one package containing Section II standalone Li-metal or Li-ion batteries per consignment. However, the U.S. Department of Transportation's Pipeline and Hazardous Material Safety Administration (PHMSA) has not yet added these restrictions to 49 CFR as yet. The PHMSA has only released a general overview of their forthcoming Interim Final Rule to harmonize with the new ICAO/IATA lithium battery restrictions. This Interim Final Rule will likely

take effect in early 2017 [56]. Although the objective of this rule is to harmonize the new regulation with international standards, PHMSA has to consider each proposed change to the HMR on its own merits, and independently evaluate the safety and economic impact of each provision.

4.3. Norms in Practice and Differences between the Norms and Regulations

On 10 February 2016, the U.S. National Transportation Safety Board (NTSB) issued two safety recommendations to "physically separate lithium batteries from other flammable hazardous materials stowed on cargo aircraft" and to establish "maximum loading density requirements" that restrict the quantities of lithium batteries and flammable hazardous materials [57]. The NTSB urged the PHMSA to take positive action on these two safety recommendations to avoid cargo fire and to give the crew extra time to safely land a cargo aircraft once the fire is detected. As a result, the U.S. Congress has given authority to the PHMSA to enforce more strict norms in the case of an on-board fire that can result from inadequate international transportation regulations.

Although many U.S. shipping carriers facilitate battery or lithium battery transportation, this section focuses on the three most popular carriers—United Parcel Service (UPS), DHL Express, and FedEx—to present an overview of the requirements for acceptance and transport of lithium batteries in the U.S. UPS is the world's largest package delivery company. When shipping lithium batteries by UPS's air service, shippers must conform to the applicable regulations published by the IATA (internationally) and/or the PHMSA (within the U.S.). However, UPS has its own additional requirements for shipping lithium batteries by air. Compared with the IATA DGRs and 49 CFR, small-size standalone lithium batteries (except lithium batteries transported according to PI968-Section IB shown in Table 4 and PI965-Section IB shown in Table 6) are not considered as UPS Dangerous Goods. Furthermore, lithium batteries for which the net quantity of each package exceeds the limits, and standalone small-size lithium batteries transported according to PI968-Section IB and PI965-Section IB all need UPS Dangerous Goods contracts prior to being transported [58,59]. Other than these special provisions, UPS transport regulations for lithium batteries are in accordance with the IATA DGR and 49 CFR.

According to 49 CFR, medium-size lithium batteries can only be transported to, from, and within the U.S. by ground. When shipping lithium batteries by UPS's ground service, shippers must comply with the international surface transport regulations (outside the U.S.) and 49 CFR (within the U.S.).

UPS transportation regulations apply to large-, medium-, and small-size standalone lithium batteries. If the gross mass of each package exceeds 30 kg, UPS Dangerous Goods contracts are necessary. In addition, small-size lithium batteries shown in Table 8 do not need to be shipped by ground as UPS Dangerous Goods. UPS transportation regulations for these large- and small-size batteries are in accordance with the international surface transport regulations and 49 CFR. However, medium-size standalone lithium batteries (gross mass of each package not exceeding 30 kg) and medium-size lithium batteries packed with or contained in equipment do not need to be transported as UPS Dangerous Goods.

DHL Express provides international express delivery services for parcels and documents. To transport lithium batteries safely by air, DHL Express shippers must comply with the latest IATA DGR, which became effective 1 April 2016. In addition, DHL Express follows its own norms based on the ICAO TI and the IATA DGR. Standalone Li-ion batteries (PI965-Section II) can be transported by DHL on passenger aircraft after approval of DHL [60]. Moreover, the consignment for lithium batteries contained in equipment (where each piece of equipment contains no more than 4 cells or 2 batteries) cannot exceed 2 packages. If this limit is exceeded, the shippers must apply for permission and use the lithium battery handling label on the package. DHL eCommerce also offers domestic and international standard parcel services, but not for Li-metal and Li-ion batteries within its international network [61]. (DHL eCommerce and DHL Express are separate companies both owned by the same parent company. DHL Express offers only international services; DHL eCommerce offers both international and domestic services.) All shippers must comply with the

latest versions of 49 CFR, the IATA DGR, the IMDG Code when shipping lithium batteries in the U.S. DHL eCommerce must approve ground transport of lithium batteries (including standalone lithium batteries and lithium batteries packed with or contained in equipment) [62,63]. Only lithium batteries contained in equipment can be shipped via DHL eCommerce's domestic expedited network.

FedEx has expanded its service by offering global freight-forwarding services. When shipping lithium batteries with FedEx's air service, all packages containing lithium batteries must strictly adhere to the ICAO TI, the IATA DGR, and 49 CFR. FedEx also has its own requirements for transporting lithium batteries. Shippers of lithium batteries must comply with all FedEx Express variations listed in the latest edition of the IATA DGR [64]. In addition, standalone Li-metal batteries prepared according to Sections IA, IB, and II of PI968 need approval prior to shipping by FedEx Express [65]. Furthermore, standalone Li-metal batteries prepared according to Section II of PI968 must have an additional FedEx Section II label [66], which is not the same as the "Cargo Aircraft Only" label shown in Figure 3b.

On U.S. airlines, the FAA rules allow passengers to carry all small-size Li-metal and Li-ion batteries in the aircraft. With the airline's approval, devices can contain Li-ion batteries with 100 Wh and 160 Wh capacity. However, spare lithium batteries of this size are limited to two per passenger and must be transported in carry-on baggage only.

5. Lithium Battery Transportation in China

Transportation of lithium batteries in China should comply with Chinese safety regulations. However, due to few available local transport regulations in China, lithium cells or batteries are currently transported in accordance with the international transportation regulations to, from, and within China.

5.1. Transportation Regulations Available in China

The Civil Aviation Administration of China (CAAC) has issued regulations on Transport of Dangerous Goods by Air (CCAR-276-R1). Lithium battery shipments by air are subject to both Chinese and international safety regulations (including the ICAO TI and the IATA DGR). CCAR-276-R1 is in compliance with the ICAO TI and the IATA DGR. The ICAO TI in the 2015-2016 edition (DOC 9284-AN/905) with corrigendum No. 1, and CCAR-276-R1 issued provisions for carrying Li-metal batteries in February 2015. The CAAC prohibits transport of standalone Li-metal batteries aboard passenger aircraft, unless the country of origin, transit state, and/or destination country grant an exemption from the prohibition. Li-metal batteries can be transported on aircraft according to the specific provisions of DOC 9284-AN/905 [67]. Furthermore, transporting standalone Li-ion batteries as cargo aboard passenger aircraft is prohibited, effective from 1 April 2016.

At present, the Chinese regulations for transport of lithium batteries by sea and ground are not sufficient. Relevant departments in China mainly follow the international regulations, including the IMDG Code, the ADR, and the RID.

5.2. Norms in Practice and Differences between the Norms and Regulations

Due to the stringent regulations of the IATA DGR for transportation of lithium batteries, Chinese airlines must follow and enforce these regulations rigorously. Chinese airlines are subject to the requirements for UN tests, parameter limits, packaging, marking, labelling, and transport documents of the ICAO TI, the IATA DRG, and CCAR-276-R1. Chinese airlines' transport regulations for low-production-run or prototype lithium batteries, lithium batteries being shipped for recycling or disposal, and damaged or defective lithium batteries are in accordance with those introduced in Section 3.2.

Chinese airlines' transport requirements for Li-metal and Li-ion batteries contained in personal devices are almost the same as those of U.S. airlines. Each spare Li-ion battery must be individually protected to prevent short circuits and carried only in carry-on baggage. In most cases, airlines permit up to two spare Li-ion batteries (more than 100 Wh, but not exceeding 160 Wh) [68]. Except for the

above common provisions, each Chinese airline also has its own requirements. For example, China Eastern Airlines prohibits shipping lithium batteries undeclared by the State of Origin, intermediate country, destination country, and air freight operator [69].

Although the transport requirements in China comply with the international regulations, there is an enforcement gap. Lithium batteries manufactured in China are often shipped internationally from Hong Kong to avoid China's oversight and dangerous goods regulations. The shipping logistics are complex and involve a ground transporter, a freight forwarder, an export agent in Hong Kong, and consolidators. The lack of surveillance and the complex logistics can raise safety issues, such as counterfeit lithium batteries shipped internationally from China and Hong Kong [70]. Therefore, safety regulations for battery transport in China should be enforced starting from the point of origin.

6. Lithium Battery Transportation in Europe

European battery transportation regulations largely follow UN regulations. Even so, as a group of nations and individual national transport authorities, the European Union has designed its own regulations with some special norms. Member states of the European Union and other European countries allow lithium cell/battery transportation only when manufacturers follow a Quality Management System (QMS) specified in ISO-9001 and ISO-1400. Sections 4.3.1 to 4.3.4 of the document describe existing Li-ion battery transportation regulations in Europe and differences between European regulations and international regulations for transport of lithium batteries. The following sections in this paper also cover norms in practice and required documents for battery transportation.

6.1. Transportation Regulations Available in Europe

In general, Europe follows international regulations such as ADR, RID, IATA, ICAO, and IMDG for lithium battery transportation by road, rail, air, and sea. Moreover, additional European agreements were established by the UNECE. These agreements, ADR and the European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN), especially address international carriage of dangerous goods by road and inland waterways.

European Standards (ENs) and regulations for lithium battery transportation mostly follow international norms provided by the UN Regulations for the Transport of Dangerous Goods category 9. Lithium battery safety and transport regulations are largely covered by two EN standards—EN 50272-1 and EN 62281:2013 [71]. EN 50272-1:2011-10 defines safety requirements for secondary batteries and battery installations. Part 1 of the EN 50272-1 standard covers detailed safety aspects, hazards associated with electricity (installation, charging, discharging, short circuits, and other points of concerns in the batteries), electrolyte, inflammable gas mixtures, storage, and transportation.

EN 62281:2013 defines the safety of Li-metal and Li-ion cells and batteries during transport. A draft version of EN 62281:2015 is now available with updates. EN 62281 specifies test methods and requirements for primary and secondary lithium cells and batteries to ensure their safety during transport. These test requirements are comparable to the tests defined in the UN Manual of Tests and Criteria, Subsection 38.3, which is discussed in Section 2. However, these standards do not cover any norms or guidelines for recycling or disposal of lithium batteries/cells. Table 14 compares UN Manual of Tests and Criteria, Subsection 38.3, and IEC-EN 62281 standards. IEC and EN standards align with each other. The other standard in practice is IEC 62485-1:2014, which closely aligns with EN 50272-1.

Table 14. Comparison of UN and IEC test criteria.

Test Criteria Standard	UN	IEC	
	Part III S38.3	**IEC 62133**	**IEC 62281**
External short circuit	●	●	●
Abnormal charge	●	●	●
Forced discharge	●	●	●
Crush		●	
Impact	●		●
Shock	●	●	●
Vibration	●	●	●
Heating		●	
Temperature cycling	●	●	●
Low pressure (altitude)	●	●	●
Projectile			
Drop		●	●
Continuous low-rate charging		●	
Molded casing heating test			
Open-circuit voltage			
Insulation resistance			
Reverse charge			
Penetration			
Internal short circuit		●	
Immersion			
Fire			

6.2. Differences between European and International Regulations

Besides the battery safety, pre-transportation testing, and transportation regulations specified in the EN and IEC standards, there are a few other regulations in practice for battery transportation in Europe. These regulations are provided by different international and national regulatory bodies and cover various modes of transportation. Section 3 summarizes the international transportation regulations that are also being used in Europe.

In addition to the above international regulations, European countries have multilateral agreements regarding various aspects of transportation and packaging of damaged, recyclable, prototype, and low-production-run lithium batteries. A few agreements make transportation of equipment containing lithium batteries easier within Europe. These multilateral agreements allow countries to have common regulations to accommodate the policies of transportation ministries within individual countries, as well as the diverse safety norms and available infrastructures (tunnels and roads) in individual countries [72]. These agreements became valid on 1 January 2017, and are subject to renewal with mutual consensus between involved parties. A few examples of multilateral agreements are given in Table 15 and described below. For further details, see reference [72].

In 2015, both the International Airlines Group (IAG), a multinational airline holding company located in Europe and Emirates Airlines banned the transport of Li-ion batteries as cargo [54]. In addition, IAG, Emirates, and a few others do not accept booking of UN3480 Li-ion batteries (as shown in Table 3) as cargo on passenger aircraft. However, this restriction does not affect batteries packed or contained in equipment (UN3481 and UN3091 as listed in Table 3). Emirates has a strict policy for carriage of Li-ion batteries and polymer batteries. Especially, Li-ion cells/batteries carried under Sections II, IA, and IB of PI965 (as shown in Tables 6 and 7) are totally restricted for carriage as of 1 April 2015. Road transportation in Europe is actually the preferred transport method for lithium batteries. Being geographically well connected through its road systems, Europe has an advantage of inexpensive road transportation that is less rigidly regulated compared to air and sea.

Table 15. Multilateral agreements between European countries.

Multilateral Agreement	Countries	Differences between Multilateral Agreements and International Regulations
M285	Germany, Italy, The Netherlands, Switzerland	The agreement allows relaxation in packing and in sizing of lithium batteries carried for disposal or recycling while they are still inside equipment and when the equipment can provide the equivalent safety. The agreement overcomes the strict requirement of international regulations on instruction P909 in Subsection 4.1.4.1 about equipment containing lithium cells and batteries.
M292	Germany, France, Austria, Spain, The Netherlands, Switzerland	The agreement allows approval by a country-based competent authority even if the competent authority is not under ADR contract. By derogation from the provisions of chapter 3.3 under SP 376 of the ADR, if Li-ion or Li-metal cells or batteries that have been identified as being damaged or defective, these products are no longer required to be tested in accordance with the applicable provisions of the UN Manual of Tests and Criteria and need approval from authority.
M294	Germany, France, Poland, Switzerland	The agreement concerns SP 310 for pre-production of large Li-ion batteries not tested under UN subsection Manual of Tests and Criteria 38.3, with the gross mass exceeding 100 kg. M294 confirms the requirement of an insulated and sturdy structure to prevent any mechanical movement while transporting pre-production shipment. Under the agreement, large pre-production batteries can be carried in a strong non-approved package that still confirms packing agreement under the treaty.
M295	Germany, France, Switzerland	The agreement provides packaging requirements for prototype or damaged cells/batteries contained in the equipment. These cells/batteries should be transported in accordance with SP 376 and packaged according to international regulations. The consignor should include the phrase "carriage agreement under the terms of Section 1.5.1 of the ADR (M295)" in the transport document.
M296	Germany, France, United Kingdom, Switzerland	The agreement defines carriage of hybrid lithium batteries that contain both primary Li-metal cells and rechargeable Li-ion cells. In the hybrid system, these batteries should not be designed for getting charged externally. In such a case, rechargeable Li-ion batteries can only be charged from the primary lithium cells. The complete system should have overcharging protection and is tested under the UN Manual of Tests and Criteria. The consignment is restricted by weight and capacity.

Air transportation of Li-ion batteries in Europe is becoming more restrictive, and battery manufacturers are encouraged to use road, rail, or sea transportation. For example, the ICAO/IATA organizations require authorization for shipments of prototypes or low-production-run cells/batteries by air. The shipper must first secure a "competent authority approval" from the appropriate transportation agency in the country of origin. In contrast, prototype batteries can be shipped by sea internationally without any approval. However, stringent packaging under provision shipments provided by the IMDG SP310 is required [73]. The requirements associated with road transportation are significantly less restrictive.

6.3. Norms in Practice and Differences between the Norms and Regulations

UN, ADR, ADN, IMDG, and IATA transport regulations are used in Europe (see Section 6.1), while, in practice, EN-IEC standards are also used for lithium battery testing before transportation. Safety regulations during transportation, goods categories, and handling are defined by various authorities such as ADR, DGR, IATA, and IMO. Norms that cover testing, safe parameter limits, and packaging are given by UN and EN.

As specified above, ADN allows bilateral and multilateral agreements among European countries for safe and reliable transportations of dangerous goods including lithium batteries. These agreements are respected within the involved parties/countries and differ from other international regulations in respect to packing and handling of damaged and/or recyclable batteries. These agreements are designed to accommodate differences between transport regulations provided by transport authorities of individual countries and available infrastructures in the countries. A few examples of multilateral agreements are summarized in Table 15.

In practice, most of the transport companies in Europe follow ADR, IATA, DRG, and UN regulations for transportation. International shipping companies such as UPS, FedEx, and DHL also follow similar regulations as described in Section 4.3. Table 16 summarizes some European countries' policies of postal services for Li-ion battery transportation. Most of the postal services allow only built-in or installed batteries. A few postal services allow uninstalled batteries as domestic post where batteries (not more than two) are kept separately from the product but packed within the same package. Uninstalled batteries generally require a material safety data sheet (MSDS) following UN 38.3 instructions [74–77]. An MSDS or product safety data sheet (PSDS) is an essential document in Europe for transporting such lithium batteries. It is a 4–6-page document that contains a product/material description, safety features, hazard identifications, regulatory information, transportation, and other miscellaneous details about handling.

Table 16. Summary of lithium battery restrictions via postal services in Europe.

Postal Company	Standalone Lithium Cells/Batteries	Lithium Cells/Batteries Packed with Equipment	Lithium Cells/Batteries Contained in Equipment
Europe Quick mail	Not allowed	Allowed with MSDS	Allowed
Deutsche Post	Not allowed	Not allowed	Not allowed
Royal Mail	Not allowed	Allowed with MSDS	Allowed with MSDS
Swiss Post	Not allowed	Not allowed	Allowed
European Special line	Not allowed	Allowed with MSDS & UN 38.3 instructions	Allowed with MSDS

7. Lithium Battery Transportation in South Korea

Lithium battery transport regulations in South Korea generally comply with international UN regulations and restrictions. However, lithium battery transport in South Korea is also under the control of the Ministry of Land, Infrastructure and Transport (MOLIT), a national government organization, equivalent to the ICAO, with the goal of strengthening the safety of hazardous materials transported by air [78]. Furthermore, regulated products must also pass Korea Certification (KC) standard testing and obtain the KC certification for transport.

South Korea's Dangerous Goods Safety Management Law also adopted UN GHS classification and labelling standards for hazardous substances (contained within the dangerous goods) that fall under the GHS physical hazards classification criteria (i.e., flash and melting points that are defined by GHS classification). For these substances, companies may use GHS labelling. However, substances not covered by such criteria (e.g., some flammable liquids with flash points that are not within the scope of GHS criteria) are subject to labelling requirements as stipulated by the law. In addition, the national standard for dangerous goods transport provides details of classification of dangerous goods following the IMDG [79].

7.1. Transportation Regulations Available in South Korea

The KC mark is a key prerequisite for lithium battery logistics in South Korea. Lithium batteries transported in South Korea should pass the KC 62133 test standard, which is harmonized with IEC 62133, and should be identified by the KC mark. The KC 62133 standard evolved from the K 62133 standard. It was established 25 July 2012 for Li-ion secondary cells and battery packs. K 62133 standard was similar to the 1st edition of IEC 62133 and covered: (1) lithium secondary cells equal to or more than 400 Wh/L; (2) batteries assembled by the cells for use in portable devices; and (3) cells and batteries for use in portable devices with a navigation function. These standards were identical except storage time for temperature cycling was only required for 24 h after testing [80]. In September 2014, the new KC 62133 standard was established with added coverage for batteries with <400 Wh/L per volume. The new KC 62133 requires testing of all Li-ion batteries irrespective of their energy density value (Wh/L). Accordingly, the old standard (K 62133) was abolished starting in August 2015. The batteries with <400 Wh/L per volume energy density became mandatory starting in April 2016 [81].

Only certified lithium batteries with the KC mark can be transported in South Korea. In-country testing is mandatory. Usually, 21 sample batteries are required to be tested over the course of 10–12 weeks, which can be conducted by the authorized laboratory collaborating with a Korean standard testing institute, such as Korea Testing Laboratory [82]. Labelling (Figure 4) requires specific details in Korean, including product name, model name, designation, nominal voltage, rated capacity, manufacturer, customer service number, and country of manufacture.

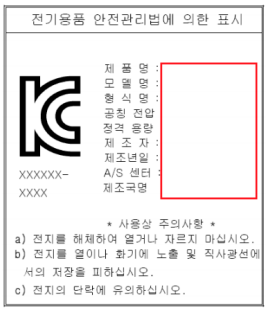

Figure 4. Shipping label with KC mark.

7.2. Differences between South Korean and International Regulations

Although KC 62133 complies with IEC 62133, the IEC standard only refers to a set of portable sealed secondary cells, and the batteries made from them, for use in portable applications. Even if the battery is already KC 62133 certified, some additional requirements for the battery system might still apply. KC 62133 does not consider the implications of integrating the battery within some larger systems, including the charging function outside the battery. Therefore, a battery system standard is needed for products such as hoverboards even when the individual batteries in the system have already been certified. Additionally, even if the battery is marked with the KC 62133 label, it does not mean that any shipment company accepts KC 62133 instead of UN 38.3 because the latter is a requirement directly from IATA for the safe transport of lithium batteries. However, in most cases, the UN 38.3 report would be provided by battery manufacturers prior to KC 62133 [83,84].

7.3. Norms in Practice and Differences between the Norms and Regulations

Different airlines in South Korea have their own norms for transportation of lithium batteries. Most South Korean airlines, such as Korean Air, Air Busan, and Asiana [85–87], clearly regulate that up to five spare lithium batteries are allowed as carry-on only and must be protected to prevent short circuits. Each battery's energy cannot exceed 100 Wh. Exceeding 100 Wh but not exceeding 160 Wh, a maximum of two spare lithium batteries are permitted as carry-on with the approval of the operator.

Two each of 100~160 Wh batteries can be included with five spare batteries. T'way Airlines permits up to four spare batteries that are less than 100 Wh as carry-on, and up to five batteries within 100 Wh mounted on the device are permitted as check-in baggage [88].

These rules are different from FAA regulations that limit spare lithium batteries (more than 100 Wh, but not exceeding 160 Wh) to two per passenger. However, even though there are no strict rules on specific battery products in South Korean airports, some products are still banned, such as portable chargers strictly restricted as spare batteries in China and e-cigarettes in Taiwan [85,87].

South Korean Air prohibits transportation of small vehicles equipped with lithium batteries, including air wheels, solo wheels, hoverboards, mini Segways, and balance wheels by either carry-on or check-in [85]. Lithium batteries within 160 Wh for consumer electronics and medical device are allowed onboard.

Air Busan has more specific restrictions for battery-powered devices. Small vehicles equipped with lithium batteries are also forbidden in either carry-on or check-in baggage. However, medical devices powered with lithium batteries, such as wheelchairs, are permitted with the following restrictions. The batteries should be removed from the wheelchair and only permitted in carry-on baggage with the approval of the operator. For devices operated by one battery, up to two batteries within 300 Wh per each are permitted; whereas for devices with two batteries, up to four batteries within 160 Wh per each are permitted [86]. T'way has the same requirement for medical devices powered by lithium batteries [88].

Air cargo companies such as Korean Air accept shipments of lithium batteries according to the UN regulations (PI965 for Li-metal batteries only, PI968 for Li-ion batteries only, PI966/967/969/970 for batteries with equipment) [89]. South Korean transport companies, covering air, road, and sea shipping, do not list the specific prohibited items on their official websites, including CJ Korea, Korea Post, Hanjin, Lotte, and KGB. South Korea Post claims that electric appliances, which are permitted by the regulation of electric appliances and telecommunications devices, need to be reported to the Ministry of Information and Communication [90]. It does not mention specific requirements for the batteries if they are equipped with the appliance. However, for electric appliances equipped with batteries to be transported in South Korea, they must be affixed with the specific label (KC certification).

8. Lithium Battery Transportation in Japan

In Japan, lithium batteries are classified as dangerous goods by the Japanese Ministry of Economy, Trade and Industry (METI). Lithium batteries are listed as "Category B" (Non-Specified Electrical Appliances and Materials) grade goods according to the DENAN law, which is the Japanese Electrical Appliance and Material Safety Law [91]. In Japan, all electronic goods (including lithium batteries) must be tested in accordance with the DENAN law [92,93]. The Product Safety Electrical Appliance & Material (PSE) mark is mandatory for products falling under the DENAN law. Regulated products must bear the appropriate mark when shipped to Japan in order to clear Japanese customs. Regulations may apply not only to the product itself, but also to packaging, marking or labeling, testing, transportation and storage, and installation. Compliance with "voluntary" standards and obtaining "voluntary" marks of approval can greatly enhance a product's sales potential and help win Japanese consumer acceptance [94]. An MSDS and a composition table are also mandatory for transporting lithium batteries in Japan.

8.1. Transportation Regulations Available in Japan

Lithium batteries shipped to Japan must be tested according to the Japanese DENAN standards. Products regulated by DENAN fall into one of the two categories: Category A products require a PSE certificate from a third-party organization; Category B non-specific products also require compliance, but they may be self-declared.

In order to issue the PSE mark (Figure 5) for specified products (Category A), the testing organization has to be authorized by METI. Lithium batteries fall under Category B of the DENAN law and therefore may be self-declared [93,95].

Figure 5. PSE mark for specified products (**left**) and non-specified products (**right**).

8.2. Differences between Japanese and International Regulations

Even though international testing procedures for lithium batteries do exist under the UN Manual of Tests and Criteria, the tests for DENAN compliance are different from the IEC 62133 standards and UN criteria, mostly exceeding the requirements for the IEC standards [91]. Exceptions apply only for lithium batteries that do not exceed an energy density of 400 Wh/L as well as batteries used in automobiles, motorcycles, medical devices, or industrial appliances. In addition to these exceptions, lithium batteries that are designed as a part of the equipment (e.g., the batteries are fixed into the appliances by soldering or other joining methods) and cannot be removed easily are excluded [96].

Before the DENAN law was introduced, the JIS-C-8714 (Japanese Industrial Standard) plus the IEC 62133 tests were used to cover all of the Japanese requirements. The overlap between the IEC standard and the DENAN law is minimal, however, the DENAN law requires testing at extreme temperatures and a significant amount of additional testing in order to achieve the PSE mark required for the Japanese market [91]. Table 17 compares the DENAN law and the IEC standards for single cell testing. Note that DENAN compliance testing requires the additional 75–95 samples of cells that are already tested by IEC.

Table 17. Comparison of the DENAN law and IEC standards for lithium cell testing.

Test Items	DENAN	IEC 62133:2012
Continuous low-rate charge	At temperature	
Vibration		
Temperature cycling		
	Charge (extremes)	Charge (extremes)
External short circuit	Test (55 °C)	
	At temperature	Test (55 °C)
Free fall		
Mechanical shock		
Thermal abuse		
	Charge (extremes)	Charge (extremes)
Crushing of cells	Test (extremes)	
	At temperature	Test (extremes)
Low pressure		
Overcharge		
Forced discharge	At temperature	
Cell protection—high charge		
Forced internal short circuit		

The DENAN law also differs from IEC standards for testing batteries (cell assemblies). Table 18 illustrates these differences. Mostly, DENAN compliance testing requires additional 29 batteries and one host battery already tested using IEC 62133.

Table 18. Comparison of the DENAN law and IEC standards for lithium battery testing.

Test Items	DENAN	IEC 62133:2012
Vibration Battery enclosure test Temperature cycling External short circuit Free fall Mechanical shock Function of overcharge protection Free fall with appliance	Charge (extremes) Test (20 °C) At temperature	Charge (extremes) Test (55 °C)

The Japanese legal system and regulatory bodies influence the transport of dangerous goods using different modes. If any question arises about transporting lithium batteries in and out of Japan, it is advised to contact the institutions mentioned in Table 19.

Table 19. Japan transportation authorities corresponding to the international regulatory bodies.

Transport Mode	Japanese Legal System	International System
Air	Ministry of Land, Infrastructure and Transport (MLIT) ➢ Civil Aviation Bureau	International Civil Aviation Organization (ICAO)
Sea	MLIT ➢ Maritime Technology and Safety Bureau	International Maritime Organization ➢ International Maritime Dangerous Goods Code
Inland (road)	Ministry of Home Affairs ➢ Fire and Disaster Agency Ministry of Health, Labor and Welfare ➢ Pharmaceutical Affairs Bureau	Inland Transport Committee (ITC) ➢ ADR
Inland (rail)		Central Office for the International Transport by Rail ➢ RID

8.3. Norms in Practice and Differences between the Norms and Regulations

Similar to other countries, some Japanese transport companies apply further restrictions on shipping lithium batteries. These companies, such as Tenso, follow the regulations provided by the Japan Post for international mail. These regulations consist of four different parts [97–99]: (1) unlike a few countries, Japan allows importing of lithium batteries; (2) batteries must be installed or built into the equipment and loose batteries are not acceptable for transportation; (3) standard norms related to the lithium battery capacity or watt-hour rated value must be met as given in Table 20; and (4) lithium batteries must be packaged as 4 lithium electric cells or 2 lithium assembled batteries per mail item.

Nippon Express is a major Japanese transport company that accepts shipments of lithium batteries according to the UN regulations. They refer to the Hong Kong Association of Freight Forwarding and Logistics for more details on the Dangerous Goods Best Practice [100]. There are a few other popular Japanese transport companies such as Sagawa Express and Yamato Transport that do not accept lithium battery shipments. Yamato Transport is Japan's largest door-to-door delivery company, and it does not even accept products equipped with lithium batteries [101,102].

Table 20. Boundary conditions for shipping lithium batteries provided by Japan Post.

Battery Classification		Standard for Batteries That Can Be Sent by International Mail	
Type	**Structure**	**Interior Content of Lithium**	**Watt-Hour Rated Value**
Li-metal battery	Electric cell	1 g or less	-
	Assembled battery	2 g or less	-
Lithium battery Lithium-polymer battery	Electric cell	-	20 Wh or less
	Assembled battery	-	100 Wh or less (must be indicated on the exterior container)

9. Conclusions and Recommendations

With advances in high-energy-density lithium battery technologies, and as a result of numerous fires and explosions of lithium batteries, the regulations concerning the transportation of lithium batteries have been dramatically changing. Today, companies and shippers must be aware of the newest requirements if they do not want disruptions in their schedules and supply chains, or unforeseen costs.

This paper presents the safety considerations for the transportation of lithium batteries with information on pre-transportation tests, packaging norms, limits on the number of packages and quantity of batteries per package, documentation requirements (package marking, labelling, transport document, and air waybill content), and other restrictions. It is noted that international and national norms and regulations for lithium battery transportation depend on the location, transportation mode, and various attributes of the battery itself. It is also noted that national and international regulations are not completely consistent with each other and differ in terminology, procedures, transport records, inner packaging, and battery-sizing categories. Therefore, knowledge of the differences is key to proper and cost-effective transportation.

The transport of lithium batteries to, from, and within the United States is governed by 49 CFR of the U.S. Hazardous Materials Regulations. Within Europe, most of the countries follow IEC European norms and regulations, which have, for the most part, been harmonized with UN regulations, but are not completely consistent with those of the United States. In addition, European countries have signed multilateral agreements to overcome international regulations related to package size requirements and the handling of damaged and recyclable cells and batteries. In Japan, shipping lithium batteries is governed by the DENAN law, which is stricter than the IEC standards. South Korea and China principally follow the international regulations, although transport of lithium batteries in South Korea must be certified by passing the KC mark (similar to IEC 62133 except the KC standard covers all Li-ion batteries irrespective of their energy density value). China requires compliance with international regulations. As the largest and fastest growing market for lithium batteries in the world, China's strict surveillance and enforcement are crucial to minimize the risk from the point of origin to the world.

It is recommended that battery manufacturers, distributors and companies/organizations involved with batteries in their supply chain should follow UN test criteria for cells, packs, and damaged and low-production-run products/systems that include batteries (although in most of the cases, production run and damaged cells are exempted from the test criteria). Companies should then check UN, IATA, ADR, and IMO regulations for packaging, marking, and labelling requirements, because regulations often have their own unique requirements pertaining to weight, size, marking and labelling per the mode of transportation. Companies must also check the regulations of the specific country/countries they will transport from, through, and into, particularly if road transportation is being used for inland transportation. Next, companies must obtain a product certification at the level of cell, pack, or for the entire battery power system, including the battery management system. Transportation regulations for final products depend on the mode of transportation and tend to be easier for road, train, and sea as compared to air; especially for low-production-runs and damaged cells. Companies must then be aware of jurisdiction limits and legal consequences in case of accidents.

In some countries such as Japan, there are defined government authorities who are responsible for accidents during transportation. Finally, companies should prepare an MSDS document and test criteria results before transportation, with the understanding that some countries need specific test criteria for their home market (e.g., Japan needs a PSE mark on the product).

Currently, the number of regulations and the differences in regulations make the logistics of battery transport time-consuming and costly. There is definitely a need to consolidate norms and regulations. Furthermore, there is a need to consolidate safety testing requirements for battery shipments that not only cover cells, but the batteries themselves and the products (equipment, systems). This effort began with the recent IEEE 1625 (Multi-Cell Mobile Computing Devices), IEEE 1725 (Cellular Telephones), and UL 2580 (Use in Electric Vehicles). Finally, there is a need for regulations that address infrastructure requirements at the transport terminals for storing battery consignments.

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Abbreviations

The following abbreviations are used in this manuscript:

49 CFR	Part 49 of the Code of Federal Regulations
ADN	The European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways
ADR	The European Agreement concerning the International Carriage of Dangerous Goods by Road
CAAC	Civil Aviation Administration of China
CAO	Cargo Aircraft Only
DGR	Dangerous Goods Regulations
ECOSOC	Economic and Social Council
EN	European Norms
FAA	Federal Aviation Administration
HMR	Hazardous Materials Regulations
IAG	International Airlines Group
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and electronics Engineers
IMDG	International Maritime Dangerous Goods
IMO	International Maritime Organization
ITC	Inland Transport Committee
JIS	Japanese Industrial Standard
KC	Korea Certification
METI	Ministry of Economy, Trade and Industry
MLIT	Ministry of Land, Infrastructure and Transport
MSDS	Material Safety Data Sheet
PSE	Product Safety Electrical Appliance & Material
PSD	Product Safety Data Sheet
NTSB	National Transportation Safety Board

OTIF	Intergovernmental Organization for International Carriage by Rail
PAX	passenger aircraft
PG	packing group
PHMSA	Pipeline and Hazardous Material Safety Administration
PI	packing instruction
QMP	quality management program
RID	Regulation concerning the International Carriage of Dangerous Goods by Rail
SAE	Society of Automotive Engineers
SOC	State of charge
SP	Special provision
UL	Underwriters Laboratories
ULD	Unit load device
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UPS	United Parcel Service

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