1. Introduction

Governments, in both developed and developing nations, have acted to improve vehicle emissions standards. Health concerns in the 1970s first resulted in limitations on volatile organic compound, carbon monoxide and nitrogen oxide emissions from motor vehicles [c2es 2014, EPA 1999]. In recent years, the focus of regulation has shifted to carbon dioxide (CO_2) because of its effect on global climate change. Various nations have enacted taxes on large engines and provided tax incentives for purchasing alternative fuel vehicles. Legislation limiting the fuel consumption and CO_2 emissions of motorized vehicles has tightened; however, the newest generation of regulations driven by the United States, the European Union, and China present not only tougher fuel consumption and CO_2 reduction standards, but also formidable financial penalties if manufacturers fail to comply. This wave of legislation spurred by the fight against climate change has arguably instigated the recent surge in development of electric and hybrid-electric vehicles.

Directly comparing the legislation in various countries is difficult because of the various standard types (e.g. fuel economy, CO_2 standard), test cycles (e.g. NEDC, US-combined) and diverse calculation methods (e.g. vehicle weight, footprint) implemented. Additionally, the various credits and exemptions available leave room for interpretation and lobbying [Arena 2014, KPMG 2010]. The calculation method of the fuel economy of electric and hybrid-electric vehicles batteries also varies between nations and throughout time (e.g. during the phase-in of the requirements) [NHTSA 2011]. Regulations also vary based on vehicle size (e.g. vans, heavy duty), but only the regulations effecting passenger cars are discussed here. Regulations for key markets are summarized in Table 1.1.

Table 1.1: Comparison of upcoming fuel consumption / CO_2 regulations including the target year, standard type, the fleet target, calculation method, test cycle and penalties [Arena 2014].

Country / Region	Target Year	Standard Type	Unadjusted Fleet Target[1]	Calculation Method	Penalties
European Union	2015	CO_2	130 gCO_2/km	Weight based corporate average	Fines
	2020		95 gCO_2/km		
United States	2016	Fuel Economy and GHGs[2]	36.2 mpg or 225 gCO_2/mi	Footprint-based corporate average	Fines
	2025		56.2 mpg or 225 gCO_2/mi		Sales Restriction
China	2015	Fuel Consumption	6.9 L/100 km	Weight based corporate average	Fines
	2020		5 L/100 km		Public proclamation

1) Set considering test cycle used
2) Greenhouse gas

As an example of the potential severity of the fines, manufacturers failing to meet the fleet average of 95 g CO_2 per kilometer in 2021 in the European Union will face fines of 95€ per gram over the 95 g CO_2 /km target for each registered vehicle. In China, import and sales bans can be hung on manufacturers. In the United States, the Environmental Protection Agency has the authority to access penalties up to $37,500 per vehicle [EPA 2009].

Though upcoming regulations are the most stringent yet, clauses exist to alleviate some of the pressure on manufacturers. In the United States and the European Union, small and midsize manufacturers are not subject to the full scope of the rules. Combinations of manufactures can also form “pools” amongst each other to reduce their fleet emissions. Innovations that effect the overall efficiency of the vehicle but are not directly measured through the test cycle can be credited toward the fleet average in the United States (Off-cycle credits) and the European Union (Eco-Innovations). These flexibilities are summarized in Table 1.2.

Table 1.2: Comparison of exemptions and flexibilities in major markets [Arena 2014].

	USA	EU	China
Derogation for small or middle-volume manufacturer	√	√	
Pooling[1]	√	√	√
Advantages for flexible fuel[2] and alternative fuel[3] vehicles	√	√	√
Advantages for advanced technology vehicles[4]	√	√	√
Eco-innovations[5]	√	√	
Banking and trading CO_2 emissions credits	√		

1) *Manufacturers may form a pool for the purpose of meeting fuel and/or emissions targets*
2) *Run on both conventional and alternative fuel*
3) *Run on exclusively alternative fuel*
4) *Electric vehicles, fuel cell vehicles and the plug-in portion of hybrid electric vehicles*
5) *Innovative technologies not captured in the test cycle*

Until now, efficiency improvements to the internal combustion engine and various vehicle components have allowed manufactures to meet the emissions standards. However, even with the efficiency improvements in gasoline and diesel engines, as well as the introduction of bio-fuels (E5, E10, E85) and natural gas (CNG/LNG), further alternatives are required to meet upcoming targets, as shown in Figure 1.1.

The so-called hybrid electric vehicle (HEV) has been applied throughout most vehicle segments to reduce fuel consumption, either with pure electric range or to support the internal combustion engine (ICE). Further electrification of the vehicle to decrease fuel consumption, such a 48 V on-board electronics or so-called mild-hybridization can also be implemented with conventional ICEs. Recently, plug-in hybrid (PHEV) technology has grown in significance because of the greater fuel saving potential, especially over the emissions test cycles currently used. PHEVs can utilize grid energy via an external plug, and have a more significant (10-50+ km) electric range. Combined with a gasoline or diesel engine, HEV and PHEV vehicles allow for fuel savings at a reduced cost compared to a fully-electric vehicle (BEV). BEVs can theoretically produce no emissions when charged with electricity generated from renewable energy, but this technology has been slow to gather a significant market share, most likely due to the high costs of the battery systems. Hydrogen fuel cell systems have been touted as the long–term solution to increased range, but they still rely on at least a small battery system [Sterner 2014a].

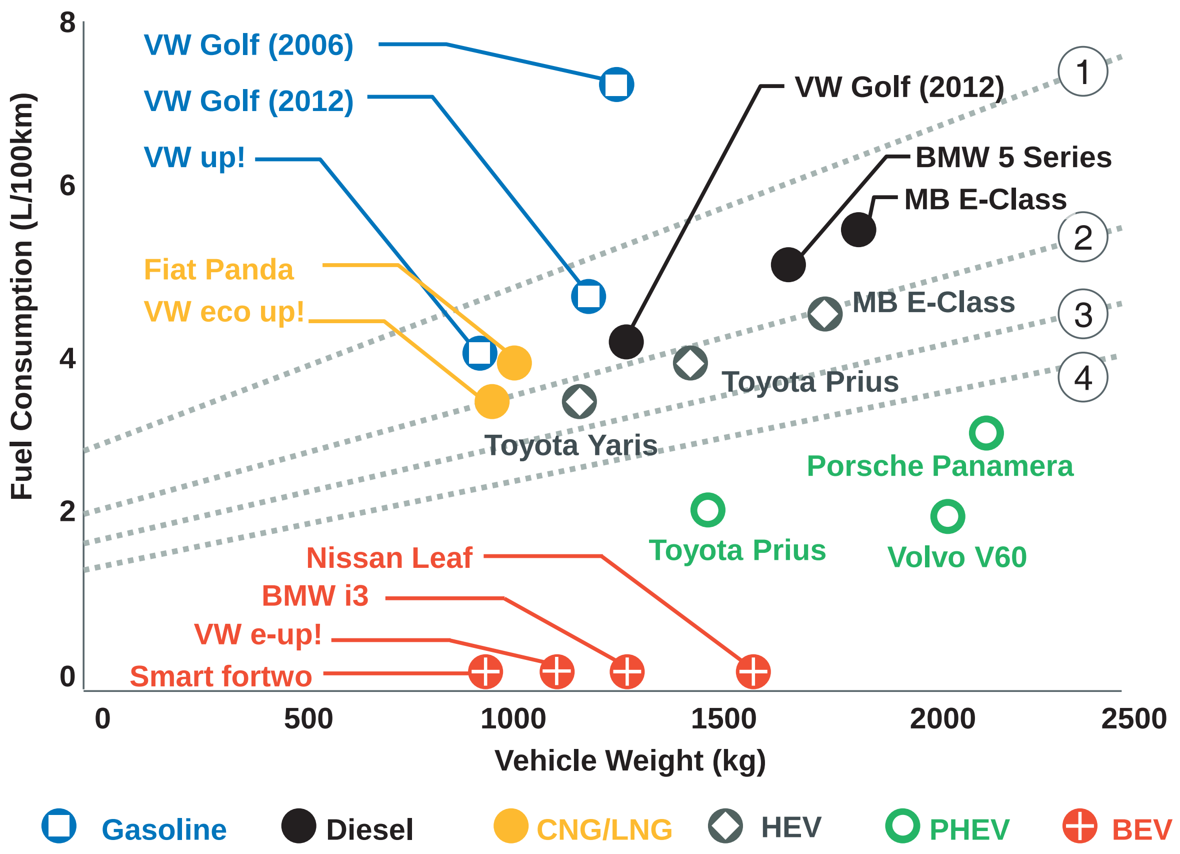

Figure 1.1: Various vehicle models grouped by drivetrain type plotted based on their fuel consumption (y-axis) and weight (x-axis) in relation to the European Union (EU) fleet targets (diagonal lines) in the years 2015 (1), 2020 (2) and proposals for 2025 (3,4). In the case of alternative fuels, a gasoline-equivalent consumption is calculated based on the energy content of one liter of gasoline [ICCT 2014].

Figure 1.1 shows the impact of PHEV and BEV vehicles in meeting EU fleet targets. Considering the development cycles for new vehicles and the recent surge in the electrification (mild-hybrid, HEV, PHEV and BEV), these advanced technology credits (see Table 1.2) will play the largest role in helping manufacturers meet the regulatory fleet targets set for the year 2020. Thereafter, as the credits are phased out, a larger fleet of fuel efficient vehicles will be required to meet regulations beyond 2020 world-wide.

1.1. Introduction to Lithium-Ion Battery Cells

The critical component in current electrified vehicles is the battery cell. Currently, Lithium-Ion cells are used. This technology was developed and successfully commercialized in consumer electronics; however, these so-called “consumer cells” were designed for small, portable devices with short lifetimes, requiring low power and designed for operation in mostly mild environments. Vehicles, on the other hand, must operate in various ambient conditions over surfaces of differing quality. Temperature extremes and rough roadways exert thermal stresses and mechanical vibrations for which most consumer electronics were never designed. Automotive cells are also orders of magnitude larger and have much higher capacities (up to 50 Ah). The target lifetimes of consumer cells (two to five years) are much less than the eight to ten-plus years required for the automotive industry [Lamp 2013].

In the quest for a automotive specific cell, various cell shapes, sizes and designs have been developed. Although the applied cell chemistries are by no means identical, they share general features. In contrast to galvanic cells (e.g. lead-acid battery) which contains solid and aqueous material states, a Lithium-Ion battery utilizes ordered structures at the positive and negative electrodes between which Lithium Ions move (intercalation). The positive electrode generally consists of a Lithium compound bound to aluminum foil, while the negative electrode consists of a carbon or graphite-based material bound to copper foil. The electrodes are separated by an electrically insulating polymer that allows the Ion transport (e.g. polypropylene or polyethylene) and surrounded by an electrolyte that aids the Ion transport. As secondary batteries, charging and discharging are repeatedly possible.

The active material used at the positive electrode and the carbon/graphite material used at the negative electrode help determine the electrochemical potential and correspondingly the energy density of the cell. Popular active materials include Lithium Cobalt Oxide ($LiCoO_2$), Lithium Ion Phosphate (LFP), Lithium Manganese Oxide (LMO), and Lithium-Nickel-Manganese-Cobalt Oxide (NMC). Different cell designs have different potentials and usable capacity ranging from 2.3-3.9 V and 110-190 Ah^1kg^{-1}, respectively [Sterner 2014b]. Additionally, different cell types respond differently to temperature and other external influences. The current standard in automotive applications is the NMC cell, as the combination of power density, lifetime, and the safety is best [Lamp 2013]. Regardless of the exact cell chemistry, Lithium-Ion cells are susceptible to various forms of aging, which results in a reduced vehicle range and battery system lifetime [Liaw 2013, Rao 2011, Vetter 2005]. Cell aging consists generally of two components: *calendrical* and *cyclical* aging [Hofmann 2014]. Calendrical aging, or aging over time, is a function of cell state of charge (SOC) and temperature. Cyclical aging, or the aging occurring during cell use, is a function of the charge / discharge rate, SOC, depth of discharge (DOD) and temperature [Sterner 2014b, Bandhauer 2014]. The focus of this research is on temperature-induced aging.

Cell aging and performance are influenced by temperature. The internal cell resistance increases with decreasing ambient temperature, especially near freezing and below. At such low temperatures (below 0°C), the cell suffers the most damage during charging due to so-called Lithium plating, which can also lead to safety risks in extreme cases [Legrand 2013, Zeyen 2013]. At such low temperatures, an inefficient discharge process also makes operation of the vehicle inefficient; however, discharging is less damaging than charging in this temperature range.

At high temperatures, the kinetics of the cell are actually accelerated, with the resulting drop in internal resistance causing an increase in available power; however, changes in the interplay between electrodes and electrolyte as well as the anode or cathode and electrolyte cause accelerated aging [Vetter 2005]. The rate of aging at temperatures above the optimal range can be approximated by the Arrhenius equation: for every 10 K temperature increase, the cell lifetime is halved [Zeyen 2013]. As the cell temperature climbs toward 90°C, electrolyte decomposition can occur, and as the temperature approaches 120°C, loss of the chemical reaction (so-called thermal runaway) is possible [Bandhauer 2011].

Not only is the average cell temperature critical, but also the temperature gradient over the cell and between cells. Uneven heat distribution has been shown to contribute to premature aging and capacity degradation by creating local “hotspots” [Lamp 2013, Fleckenstein 2012, Pesaran 2013, Kim 2007]. Temperature differences between cells cause the cells to age at different rates due to the electrical circuitry: in a chain of cells connected in series, the weakest cell lowers the system voltage [Koehler 2013]. For this reason, both the average temperature and the temperature differences must be considered in battery thermal management system (BTMS) design. The temperature dependency is explained in greater detail in Section 2.1.

Furthermore, with three different cell layouts (cylindrical, prismatic and pouch) available in a plethora of cell geometries and capacities, a multitude of unique thermal management challenges have been created. The internal layout of the cell influences the heat generation and therefore aging [Bandhauer 2011]. The various shapes require different solutions for contacting the thermal management system to the cell. Workgroups are in place to determine a single international standard (SO/IEC PAS 16898) for electric vehicles because currently various standards exist, including the 18650 cylindrical cell and the PHEV-2 prismatic cell (DIN Standard 91252) considered in this research [Lamp 2013].

The cell alone is by no means suited for vehicle integration: to function, automotive Lithium-Ion cells required a monitoring and control system, a mechanical housing, and connections to other high-voltage components [Sterner 2014b, Hofmann 2014, Koehler 2013]. Depending on the application, a thermal management strategy may also be required. Most vehicle manufacturers therefore rely on an intermediary building block, a so-called battery module, shown in Figure 1.2 [Koehler 2013, Kampker 2014].

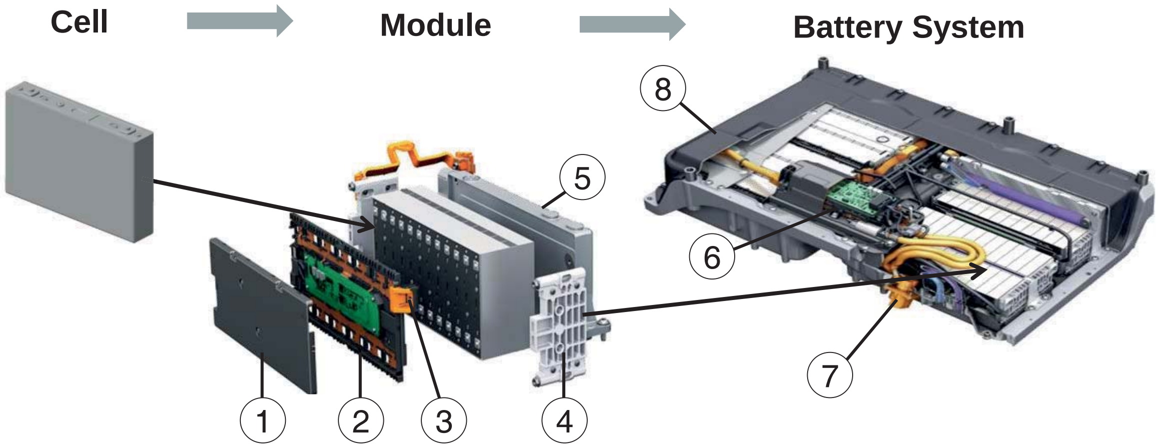

Figure 1.2: Levels of abstraction of a typical battery system: a cell (left) integrated in to a module (center) showing the cell module controller and integrated electrical contacts (1+2), the electrical connection between modules (3), the mechanical compression (4) and a cooling plate (5). The battery system (right) consisting of multiple modules housed in a casing (8) with additional power electronics (7) and the high-voltage connection to the vehicle (6). Parts adopted from [Audi 2014].

A battery module consists of any number of cells. The number of cells, combined with the circuitry chosen to connect them, determines the current and voltage of the module. Due to more stringent worker safety requirements above 60 V, the production process may be simplified by keeping the voltage below this threshold as long as possible in the assembly of a battery system. An additional consideration may be a module layout that can be used for future 48 V on-board circuitry. Regardless of the module size chosen, the same basic requirements must be fulfilled to facilitate safe operation. First, the cells must be contacted over their terminals electrically; however, no other portion of the cell may come in direct contact with another cell due to the potential for short circuiting. Additionally, some cells types exert high mechanical forces, requiring a compressive member around the cells. Depending on the location of the battery system in the vehicle, the casing required may need to absorb high crash loads, dampen vibration, and protect against corrosion from road debris [Lamp 2013, Koehler 2013]. Furthermore, a monitoring and control system is especially important for Lithium-Ion cells, which are prone to over-charging, deep discharging and short circuiting [Hofmann 2014]. Access for service or maintenance, recycling, and other end-of-life procedures must also be considered in battery system design. Depending on the vehicle use case, a thermal management strategy may be necessary, requiring the integration of additional components within the module, battery system, and vehicle. The integration of Lithium-Ion cells in a vehicle is a complex process, requiring expertise in various fields of technology.

The goal of battery thermal management is to protect against undesirable temperatures and temperature gradients across battery systems and individual cells in order to extend system lifetime, increase vehicle range, and protect against dangerous thermal states. However, thermal management systems can add size and weight to a battery system or require increased energy consumption (e.g. a fan or coolant pump), resulting in a