PROSPECTS FOR SUSTAINABLE MICRO-FACTORY RETAILING IN CANADA

PROSPECTS FOR SUSTAINABLE MICRO-FACTORY RETAILING IN CANADA: A CASE STUDY OF 3D PRINTED ELECTRIC VEHICLES

By STEPHEN QUINN HACHEY, B.Sc.

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AUTHOR	Stephen Quinn Hachey Bachelor of Environmental Science (McMaster University, 2014)
SUPERVISORS	Professor K. B. Newbold and Professor P. S. Kanaroglou
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Abstract

The contemporary global automotive industry has persisted, relatively unchanged, since its inception over a century ago. However, it appears that major changes may be underfoot with increasing environmental, social, and economic pressures to improve the industry's long-term sustainability. An alternative model, known as Micro-Factory Retailing (MFR), guided by the emerging field of Industrial Ecology (IE) has been proposed as a possible solution to the industry’s sustainability crisis. This thesis will explore the prospects of MFR in Canada and propose the use of 3D printed electric vehicles as a means to facilitate sustainable system innovation. To demonstrate the feasibility of this proposed technological pathway, three entrepreneurial firms attempting to disrupt the way in which cars are made, sold, and used will be studied. Although the timeline of such a major transition is currently unknown, Canada should act proactively to transition its role in the global automotive sector and lead the way towards a more sustainable automotive ecosystem through MFR.

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To all of you, this thesis is dedicated.

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List of Abbreviations

3D....Three Dimensional

ABS .... Acrylonitrile Butadiene Styrene

AFV.... Alternative Fuel Vehicle

AI .... Artificial Intelligence

APU.... Auxiliary Power Unit

ARB ....Air Resource Board

BAAM.... Big Area Additive Manufacturing

BC ....British Columbia

BEV.... Battery Electric Vehicles

BEVx.... Extended-Range Battery Electric Vehicle

BTO.... Build-to-order

BTS .... Build-to-stock

BRIC ....Brazil, Russia, India, and China

CAD .... Computer Aided Design

CAFE ....Corporate Average Fuel Economy

CAPC .... Canadian Automotive Partnership Council

CARB.... California Air Resource Board

CBA .... Cost Benefit Analysis

CCAP ....Climate Change Action Plan

Cd.... Coefficient of Drag

CF.... Carbon Fibre

CNG ....Compressed Natural Gas

CO .... Carbon Monoxide

CO_2....Carbon Dioxide

CUV .... Crossover Utility Vehicle

DDM ....Direct Digital Manufacturing

DFA....Design for Assembly

DIY .... Do-It-Yourself

EIP .... Eco-Industrial Park

EPA .... Environmental Protection Agency

EU .... European Union

EV .... Electric Vehicle

EVIP .... Electric Vehicle Incentive Program

FCA .... Fiat Chrysler Automobiles

FDI .... Foreign Direct Investment

FDM .... Fused Deposition Modeling

FRP .... Fibre-reinforced Polymer

FTA .... Free Trade Agreement

EM .... Electric Mobility

EBITA .... Earnings Before Interest, Taxes, and Amortization

ELV .... End-of-Life Vehicle

GDP .... Gross Domestic Product

GHG .... Greenhouse Gas

GM .... General Motors

GST .... Goods and Services Tax

GWP .... Global Warming Potential

HC .... Hydrocarbons

HFCV .... Hydrogen Fuel-Cell Vehicle

HHI .... Household Income

HOT .... High Occupancy Toll

HOV .... High Occupancy Vehicle

HPC .... High-Performance Computing

HST .... Harmonized Sales Tax

ICE .... Internal Combustion Engine

ICEV .... Internal Combustion Engine Vehicle

IE .... Industrial Ecology

IMTS .... International Manufacturing Technology Show

JIT .... Just-In-Time

LCA .... Life cycle Assessment

LM .... Local Motors

MaaS .... Mobility-as-a-Service

MFR .... Micro-Factory Retailing

MLP .... Multi-Level Perspective

MMAM .... Multi-Material Additive Manufacturing

MPG .... Miles per Gallon

MQB .... Translates from German to Modular Transverse Matrix

MSRP .... Manufacturer’s Suggested Retail Price

MY .... Model Year

NAFTA .... North American Free Trade Agreement

NAS .... National Academy of Science

NHTSA .... National Highway Traffic Safety Administration

NO_x .... Nitrogen Oxides

OEM .... Original Equipment Manufacturer

PEV .... Plug-In Electric Vehicle

Pb .... Lead

PM .... Particulate Matter

PNGV .... Partnership for a New Generation of Vehicles

PSS .... Product-Service-System(s)

ROI .... Return on Investment

SCP .... Sustainable Consumption and Production

SCR .... Selective Catalytic Reduction

SUV .... Sports Utility Vehicle

TaaS .... Transportation as a Service

TCO..Total Cost of Ownership
TMMC .... Toyota Motor Manufacturing Canada
TNGA ....Toyota New Global Architecture
TPB ....Theory of Planned Behaviour
TRIAD ....Refers to the United Sates, Western Europe, and Japan
UAW...United Automobile Workers
ULEV ....Ultra-Low Emission Vehicles
UNIFOR...Canada's Largest Private Sector Union
VAT ....Value Added Tax
VER... Voluntary Export Restraints
VMT...Vehicle Miles Travelled
V2G..Vehicles-to-Grid
VM ....Vehicle Manufacturer
VW...Volkswagen
WCED..World Commission on the Environment and Development
WTO ....World Trade Organization
ZEV...Zero-Emission Vehicle

Chapter 1 Introduction

1.1 Justification of Research Topic

It is undeniable the level with which automobiles—and the global industry that produces them—have affected nearly every facet of daily life. This was emphasized by Wells and Nieuwenhuis (2012, p.1682) when they suggested that “car-dependency has literally been built into the fabric of contemporary life” due to its direct impact on spatial, physical, social, and economic structures, its influence on patterns of urbanization, and on societal perceptions of mobility. Particularly in the United States (US), it has been argued that highways have hastened the demise of cities, draining their tax base by facilitating the outward migration of wealthier residents to the suburbs (Stromberg, 2016). The Interstate Highway System that spans the US cost $425 billion in public funds over a half century to build and led to the demolition of entire neighbourhoods for the construction of giant interchanges and the fragmentation of communities now isolated by “ribbons of asphalt” woven through the urban landscape (Stromberg, 2016).

The car’s immense social influence has premised the physical separation of work, home, leisure, shopping, education, and other activities further entrenching the role of the car in contemporary life. Beyond its functional role in facilitating mobility, however, the car has also established itself as a cultural symbol of personal freedom (Wells & Nieuwenhuis, 2012). Nearly every car trip results in some form of social or economic transaction that benefits quality of life, through access to markets, services (such as healthcare), employment, and education (OAIC, 2017). The car has become so deeply embedded within the contemporary life of industrialized nations that any potential alternative seems almost inconceivable. Yet, the negative impacts associated with the use and manufacturing of cars only become more pronounced as their role within society expands. Incremental technological improvements to address vehicle emissions in the automotive industry, for instance, have predominantly been offset by an increase in the number of vehicles on the road, heavier vehicles with more advanced features and equipment options, larger engine sizes, more frequent trip taking, and longer average trip distances (Köhler, Whitmarsh, Nykvist, Schilperoord, & Haxeltine, 2009). The lack of progress achieved through incremental innovations reinforces the need for more radical changes in the transport system to facilitate a regime transition to a more sustainable alternative (Kemp & Rotmans, 2004 as cited by Nykvist & Whitmarch, 2008).

As one of the largest manufacturing sectors in the world, producing more than 72 million passenger vehicles in 2016, the global automotive industry's influence extends far beyond national borders and is a key generator of wealth and employment in industrialized nations (OAIC, 2017; Wells & Nieuwenhuis; 2012). In Canada for instance, vehicle assembly and parts manufacturing directly contributed nearly $18.2 billion to Canada's gross domestic product (GDP) in 2016 (Statistics Canada, 2017). The Canadian automotive industry's contribution to Canadian manufacturing GDP is second only to food products (Sweeney, 2017). Between 1997 and 2007—prior to the sharp economic decline of the financial crisis—the Canadian automotive industry regularly contributed over $21 billion per annum to national GDP. Direct employment in the industry was upwards of 120,000 workers in 2014, albeit this was significantly lower than the industry's peak in the early 2000s with over 175,000 workers (Sweeney, 2017).

South of the border, 322,000 Americans were employed directly by original equipment manufacturers[1] (OEMs) in 2015 while the automotive supply and dealer networks accounted for an additional 521,000 and 710,000 secondary/intermediate jobs, respectively (Hill, Menk, & Cregger, 2015). The automotive industry in the US has historically contributed between three and 3.5 percent annually to the country's GDP. Employment "spin-off" and "multiplier" effects in the automotive sector are particularly strong because of complex supply networks and downstream spending effects (Stanford, 2014). Spin-off or expenditure-induced employment results from direct and intermediate automotive sector employees spending money and creating jobs in other, unrelated industries. Hill and colleagues (2015) estimated that for every OEM job, nearly seven additional jobs are created within the US economy, while each automotive sector job (direct and indirect) nearly creates an additional four jobs in other sectors of the economy. The large economic impact associated with direct, intermediate, and spin-off employment in the automotive industry often afford it a disproportionate level of socio-political influence despite issues of overcapacity and poor profitability (Papatheodorou & Harris, 2007). Governments have been known to offer generous subsidies and incentives to attract auto sector investments and jobs (Papatheodorou & Harris, 2007).

The automotive industry epitomizes the fundamental challenge of reconciling environmental, social, and economic needs simultaneously (Wells & Orsato, 2004). The growing

[1] Herein OEM will be used interchangeably with vehicle manufacturer (VM) and automaker.

concern over air quality, especially in populated urban centres, has prompted some governments to legislate emissions requirements. In addition, concerns over climate change have resulted in the legislation of Corporate Average Fuel Economy (CAFE, *pronounced café*) standards for new vehicles and minimum proportional sales requirements for zero-emission vehicles (ZEVs) and ultra-low emissions vehicles (ULEVs). Despite signs of ecological modernization in the automotive industry, defined by Wells and Orsato (2004) as "the internalization of ecological responsibility, the implementation of anticipatory planning practices, and the switch to the use of cleaner technologies" (p. 373) one-question remains: Is the current structure of the automobile industry conducive to long-term sustainability? A growing body of research suggests that perhaps the contemporary automotive industry's current production and consumption paradigm is incompatible with the sustainability goals of an "ecologically modern" industrial system.

Furthermore, the joint impact of tightening environmental regulations and increasing social pressure have cast doubt over the industry's ability to increase its economic and environmental sustainability within the confines of its prevailing paradigm. For instance, the industry's inability to adjust to the sudden changes in demand following the 2008 financial crisis highlights the difficulties in operating within the existing paradigm. Both GM and Chrysler sought financial assistance from the federal government in the US and Canada to facilitate their restructuring. Ford did not enter bankruptcy or receive government financial support; however, there were serious concerns over whether the company could survive without GM and Chrysler, given the numerous shared part and component suppliers between them. The ripple effect of those plant closures on the supply network would have severely strained Ford's ability to continue its own North American operations.

It is important to note that the industry's economic turmoil did not begin with the global financial crisis, although that event illustrated the inherent vulnerabilities of the existing paradigm. Perpetual overcapacity and dwindling consumer demand in mature markets like Western Europe challenged the industry's profitability prior to the financial crisis with some automakers posting operating losses over several consecutive years. General Motors' Opel and Vauxhall brands posted their 17th consecutive loss in 2015 (Sylvers & Boston, 2016). It was announced in 2017 that GM was selling its European division to French auto manufacturing group PSA, which oversees Peugeot, Citroën, and new luxury brand DS automobiles, in a deal worth €2.2 billion (PSA Group & GM, 2017). Industry analysts have suggested that it may be many years before mass-market car manufactures in Western Europe see any significant increases in their profitability margins. Despite its recent acquisition, PSA Group sought financial assistance from China's state owned Dongfeng Motor Group and the French government back in 2014 after several years of consecutive losses to reorganize its corporate structure and reduce its debt load (Sylvers & Boston, 2016; Bloomberg, 2014).

Although more sustainable mobility already exists in the form of shared mobility and public transportation, there has yet to be significant mode shifts towards these alternatives in the face of ubiquitous personal automobility[2] in most mature markets—reinforced by the prevailing socio-technical paradigm. It remains unlikely that public transportation alone will be able to address increasing levels of GHG emissions and rising air pollution in the global transport sector. As such, there is a critical need to develop more sustainable forms of personal mobility. Likewise, there appears to be a growing consensus that a paradigmatic shift and technological regime transition is necessary in the automotive industry in order for it to become more sustainable in the future. What appears to be far less conclusive is how exactly such a transformation would occur and what a future, more sustainable automotive ecosystem would look like.

1.2 Understanding the Concept of Sustainability

The logical essence of sustainability's contemporary definition can be traced back to various religious teachings, medieval philosophies, and traditional beliefs, which largely emphasized the idea of "living in harmony with nature and with one another" (Mebrutu, 1998, p. 518). At its most basic level, sustainability applies to any system or activity that can be continued indefinitely (Nienwenhuis, 2014). Sustainability, however, is often discussed in the context of development within national and international policy documents such as the United Nations sponsored 1987 report, *Our Common Future*, by the World Commission on the Environment and Development (WCED), which defined the term "sustainable development" as "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 43, as cited by Nieuwenhuis, 2014). A wide spectrum of definitions and interpretations has since risen out of the relative vagueness and ambiguity of

[2] The use of automobiles as a primary means of transport.

the WCED definition (Mebratu, 1998). The concept has generally come to be conceptualized in both government and in business as a balance between the economic, social, and environmental impacts of human activities (Nieuwenhuis, 2014).

The concept of sustainability has also been applied to patterns of human consumption and production. The term "sustainable consumption and production" (SCP) has been defined as:

The use of services and related products which respond to basic needs and bring a better quality of life while minimising the use of natural resources and toxic materials as well as the emission of waste and pollutants over the lifecycle of the service or product so as not to jeopardise the needs of future generations (ISSD, 1994 as cited by UNEP, 2015, p. 10).

Similar to sustainable development, SCP emphasizes the needs of future generations and the importance of decoupling economic growth and the use of natural resources in order to limit the degradation of the natural environment. Other principles of SCP include a focus on all phases of product life cycles and the idea that re-bound effects, which arise when gains in resource efficiency are essentially canceled out by commensurate increases in consumption, should be avoided or minimized to the greatest extent possible (UNEP, 2015). The concept of SCP highlights the critical importance of addressing both systems of production and consumption when attempting to achieve sustainability within industrial system, such as the automotive industry.

1.3 Towards Sustainability in the Automotive Industry

In an effort to explore what a more sustainable—and ecologically modern—paradigm for the automotive industry could look like, researchers from the Cardiff Business School in Wales, UK, namely Paul Nieuwenhuis and Peter Wells, explored the concept of Micro-Factory Retailing (MFR), a theoretical business model rooted in decentralized and distributed economics (Nieuwenhuis, 2014; Nieuwenhuis, 2008; Wells & Orsato, 2005; Wells & Orsato, 2004; Wells & Nieuwenhuis, 1999). Central to their argument against the viability of the current automotive paradigm is the primacy of least cost manufacturing economies of scale within the prevailing business model. The industry's dominant production technologies have remained relatively unchanged since the inception of mass automobile production nearly a century ago. Contemporary vehicle design remains centred around the all-steel unibody, while conventional gasoline and diesel fuel internal combustion engines (ICEs) predominate. The researchers have argued that this technological monoculture—characterized by inefficient ICEs, high capital costs, and high entrance barriers—stifle radical innovation and impede meaningful improvements to the industry’s overall sustainability. Under the combined pressure of increasing regulations, shifting patterns of demand, and evolving consumer attitudes and preferences, there is growing uncertainty over the future viability of the current paradigm, locked-into a potentially unsustainable technological regime.

A caveat of the proposed MFR model is that it cannot be effectuated within the existing technological regime. The MFR framework is based on small-scale, distributed manufacturing sites that are incompatible with the high production volumes necessary to amortize the high capital costs of current production processes and product technologies. Aside from acknowledging the need for a technological regime transition, the literature on MFR in the automotive industry did not initially present a suitable alternative to facilitate the transition. Richardson, Will, and Napper (2015) were the first to explore an alternative vehicle design for distributed micro-factory production, a hallmark of the MFR business model. The researchers highlighted the future production possibilities and manufacturing practices being forged ahead by “a new and diverse breed of tech/artisan-derived transport providers emerging from outside the existing industry” (Richardson, Will, & Napper, 2015, p.1).

Alternatively, Williams (2006) put forth the idea that the path to sustainability in the automotive industry lies perhaps in functional and systemic level changes rather than in technological innovations at the product or process level, which tend to be the focus of most sustainability solutions in the automotive industry. The concept of product-service systems (PSS) is put forth as a means of achieving such functional and systemic changes as it is predicated on new arrangements for product ownership and stewardship, and new producer-consumer interactions. Simultaneously, Williams (2006) argued that small-scale manufacturing sites as described by the MFR concept and dependent upon novel approaches to vehicle design and production could effectively facilitate the adoption of full scale PSS in the automotive industry at a local scale. Collectively, there appears to be some rather compelling synergies between these concepts and perhaps an opportunity for a more sustainable path for the future of the automotive industry.

The political climate and market for electric vehicles (EVs) appears to be changing rapidly, with widespread electric mobility (EM) potentially on the horizon. France and Britain were the first two countries to make an unprecedented pledge to ban the sale of gasoline (petrol) and diesel ICE vehicles by 2040 (Asthana & Taylor, 2017). Automotive OEMs also appear to be on their way towards embracing alternative propulsion technologies, specifically electrification, as a means to satisfy increasingly stringent fuel economy regulations and consumer demand for more environmentally conscious products. Perhaps in an effort to compete with the likes of Tesla Motors (which began production of its first foray into the mass market with the all-electric extended range Model 3 in June of 2017) several incumbent automakers have announced new strategies for the development of future production EVs, signaling rapid change in the EV market.

Luxury vehicle manufacturers (VMs), in particular, seem keen to offer an alternative to Tesla's premium EV offerings. Noteworthy examples include Mercedes-Benz and Volvo. Mercedes-Benz unveiled the name of an all-new EM sub-brand named EQ and a close-to-production sports utility vehicle (or SUV) concept. Volvo Car Group announced that every new vehicle launched beyond 2018 would be equipped with an electric motor, signaling the end of ICE only vehicles; moreover, Volvo's current performance arm, Polestar, will be re-branded as its own standalone global electrified performance car company (Mercedes-Benz, 2017; Volvo Cars, 2017a; Volvo Cars, 2017b). In the mass market consumer space, GM debuted its own all-electric extended range vehicle named the Bolt in advance of the Model 3, and Nissan recently debuted the second generation Leaf with an enhanced all-electric range. Reluctantly or not, the industry seems to understand that EM will have a pivotal role in the future and is eager to gain a competitive advantage.

1.4 The Prevailing Paradigm and the Origins of Mass Production

The automotive industry's current production and consumption paradigm is well established, having dominated the industry with relatively few changes to its core business model over the last century. All major global VMs rely principally on revenues generated from the sale of new vehicles and their associated finance and lease agreements (Wells & Orsato, 2004). This business model requires strong and persistent demand from geographically expansive markets to support a capital-intensive production process (Wells & Orsato, 2004; Wells & Nieuwenhuis, 2004). Large, centralized manufacturing facilities characterized by elaborate and geographically expansive supply networks transport finished vehicles to a dense network of distributed retail franchises operated under the manufacturer's brand in order to reduce costs (Wells & Orsato, 2004). As such, OEMs do not conventionally participate in downstream revenue opportunities throughout the life cycle of their vehicles including maintenance; post-production customization; retrofitting or upgrading; and recycling and disposal (Wells & Orsato, 2005).

1.4.1. Henry Ford's Continuous Flow Manufacturing

The history of the automobile industry is often divided into three distinct periods, each representing significant structural changes in the automotive industry: Craft Production, Fordism (i.e., Mass Production), and Lean Production (epitomized by the Toyota Production System [TPS]). Craft production techniques were used by the world's first specialty automobile manufacturers in Europe beginning in the late 1880s (Womack, Jones, & Roos, 1990). Automobiles were assembled one-by-one using handmade parts by skilled craftsman. Each vehicle was distinct due to the "dimensional creep" that occurred as each subsequent part was made to fit onto the assembly leading to poor durability and reliability (Womack et al., 1990). This process was time consuming and expensive as production was limited to only a few hundred units per annum. Car ownership was exclusive to the upper class, who often valued speed and customization primarily over cost, drivability, and maintenance (Womack et al., 1990).

The introduction of car ownership to the mass market was the impetus for the industry's first paradigmatic shift, pioneered by Henry Ford, the founder of the Ford Motor Company. Several pivotal innovations, including advancements in machine tooling capable of working with pre-hardened metals, lead to the standardization of parts and mass production, which lowered costs and improved quality and reliability. When the Ford Model T first entered production in 1908, skilled fitters performed a sequence of activities lasting 514 minutes on average at a stationary assembly stand. Improved part interchangeability, simplicity and ease of attachment allowed Ford, by 1913, to successfully reduce the average task cycle of a factory worker to just 2.3 minutes by having them perform just a single simple task before moving on to the next assembly stand to perform the same task again (Womack et al., 1990).

Ford realized even greater efficiencies at the Highland Park plant in Detroit, MI with the introduction of the moving/continuous flow assembly line that allowed workers to remain stationary as vehicles moved along a motorized assembly line, reducing the average task cycle to just 1.19 minutes. Although “the complete and consistent interchangeability of parts and the simplicity of attaching them to each other” (p. 26) enabled the moving assembly line, it was the division of labour on the factory floor and worker’s familiarization with simplified tasks that maximized production efficiency (Womack et al., 1990). This dramatically reduced the amount of labour required to assemble each vehicle and created economies of scale in production (the process by which unit costs are reduced by increasing the rate of production). The cost of manufacturing remained relatively unchanged as the rate of production increased, allowing the fixed costs of manufacturing to be spread out over a greater number of individual units. The design of the Model T was influenced by its production process (lending to its ease of use and manufacture) which, allowed it to be produced more cheaply despite improvements in quality relative to craft production (Womack et al., 1990).

1.4.2 Alfred Sloan’s Management Strategy

In spite of laying the foundation for modern mass production and vehicle design, Henry Ford’s competitive advantage over craft-producers was eventually outdone by competing automakers. Henry Ford’s rigid pursuit of least unit cost production initially awarded him market dominance by undercutting the competition on price (Holweg, 2008). This rigidity and a reliance on a single strategy contributed to Ford’s inability to respond swiftly to new market demands and new competitive pressures (Holweg, 2008). Ford’s market leadership ended in 1927 when it was overtaken by General Motors (GM) with the help of their new president, Alfred P. Sloan, who perfected the modern mass production system by introducing a decentralized organizational structure and by satisfying the market’s demand for choice and product variety (Holweg, 2008). Ford’s strategy to provide a vehicle at unrivalled cost “in any colour as long as it was black” was undercut by Sloan’s ability to provide “a car for every purse and purpose”. Sloan introduced the concept of “planned obsolescence” and cultivated consumer loyalty by creating a ladder of success through a multi-level brand strategy allowing consumers to upgrade to a more luxurious model with a more prestigious brand image gradually as they became more affluent with age.

Product standardization was a pillar of Ford’s production strategy to drive down costs continuously and to sell vehicles based on price alone. Sloan’s more flexible product strategy accomplished this by standardizing mechanical components across the entire vehicle range and by investing in dedicated tooling that would be used to manufacture the same vehicles over several years. In order to expand the market and gain market share, Sloan pioneered the concept of consumer credit and installment paying, and introduced model cycles with annual design changes. Superficial changes to a car’s exterior or interior appearance were used to generate consumer demand while manufacturing economies of scale were maintained through the car’s major underlying structural and powertrain components, which remained predominantly unchanged for several iterations of a model (Wells & Nieuwenhuis, 2012). Today's contemporary VMs continue to operate in line with both Ford’s and Sloan’s production and management strategies (Wells & Orsato, 2004).

1.4.3 Edward Budd’s All-Steel Car Body

One of the main tasks of a contemporary automotive assembly plant is to manufacture all-steel car bodies, which are then painted and later assembled into finished vehicles. Nieuwenhuis and Wells (2007) suggested that the steel car body is the single most important engineering and marketing component of a modern automobile. Not only are all the parts and components of a vehicle fixed onto its body, it is also the primary design feature and marketing tool used to distinguish between vehicle models and attract consumer interest. Unlike mechanical components like engines or transmissions, which often span more than one model in an automaker’s line-up and endure for several design cycles with only minor adjustments, car bodies require continual investment to accommodate regular aesthetic changes (Nieuwenhuis & Wells, 2007).

As a production technology, the all-steel body helped reduce labour requirements and drove down unit costs when combined with Ford’s production strategy on the factory floor. The high capital cost required for the manufacture of steel car bodies also represents a major barrier to entry. Investments in steel-pressing and body shops often impede the entry of new firms, while also prohibiting incumbent firms from exiting the market or making significant changes to their existing practices (Nieuwenhuis & Wells, 2007). These investments can only be recuperated over time through large production volumes that are often initially unachievable by small car firms entering the market for the first time.

Numerous factors throughout its history have influenced the trajectory of the automotive industry, culminating in its current state. Changes related to the organization of labour (including the division of labour, skill and work cycles) and labour-management relations, are often cited as being the foremost motivators for the Fordist era of mass production (Nieuwenhuis & Wells, 2007). In their account, Nieuwenhuis and Wells (2007) did not attempt to refute this history; rather the authors wished to identify and outline the role that technology has played within this narrative, specifically the co-evolution of innovative products and processes. Other contemporary perspectives that have considered the role of technology in mass production have focused exclusively on the role of the ICE and the moving assembly line (Nieuwenhuis & Wells, 2007). For instance, Alfred Chandler, Jr.'s analysis of the changes that made both mass production and manufacturing based corporations feasible in the US is widely accepted within the field. However, it credited the improved managerial skills and practices that allowed the benefits associated with economies of scale to be realized through the exploitation of ICE technology and the continuous-flow manufacturing process.

Nieuwenhuis and Wells (2007) suggest that this narrative is incomplete and that business historians have collectively ignored the fundamental contributions of Edward Gowan Budd and his all-steel "monocoque" or "unibody" that evolved alongside Ford's production strategy. Parallel innovations in press technology, vehicle design, welding systems, body framing fixtures and jigs, steels, and paint all enabled the unification of the car chassis and body and the secondary benefits it provided. The all-steel design was stronger and stiffer than traditional composite bodies that were made of wood and steel and allowed greater flexibility in vehicle design. Nieuwenhuis and Wells (2007) posited that along with the ICE, Budd's all steel body is one of the core technologies that enabled mass production. Their analysis emphasized the co-development of product design (Budd's all-steel unibody) and production technology (continuous-flow manufacturing) in describing the industry's trajectory and establishing contemporary automotive manufacturing practices.

Ford had originally resisted the use of this new technology, insisting that the added time needed to heat and cool the pressed steel was wasteful and instead favoured the casting process used for composite bodies. Ford instead pursued a decade of incremental improvements to his production process before conceding to the advantages of the all-steel unibody in 1925. Ford's resistance towards radical innovation due to sunk investments in the existing technology and production process was compounded by the vertical integration of the supply chain, which was designed to reduce costs and the risk of supply shortages. Together, these factors helped maintain the existing technological regime.

The high degree of outsourcing by contemporary automakers means that manufacturing economies of scale are often achieved in the production of all-steel bodies, engines, and transmissions. Car bodies are also the core design element that differentiate vehicles from competing automakers and is a key marketing tool for new vehicle models (Nieuwenhuis & Wells, 2007). The high capital intensity of all-steel body production often determines the minimum level of production necessary to recuperate these costs. Assembly plants typically aim to maintain annual production level of at least 200,000 vehicles to achieve competitive per unit costs (Stanford, 2014). The increased level of automation within the production of all-steel bodies has also increased the capital cost involved with setting up a production line. Although many global automakers also manufacture their own engines and transmissions, the pressing and painting of car bodies still demands the largest proportion of capital investments. For this reason, automakers restrict the activities in their assembly plants to press and paint shops, and vehicle trim and final assembly. The significance of the all-steel body in modern automobile production suggests that achieving sustainability in the automobile industry will require an alternative production technology to replace the use of capital-intensive all-steel bodies.

1.4.4 Lean Production and the Toyota Production System

The second major shift in automotive production began in the 1950s when Japan's newly established Toyota Motor Corporation developed a mass production strategy tailored to their smaller facility and that required less capital (Nieuwenhuis, 2014). Toyota did not initially have the capital necessary to emulate the Ford-Budd production system, which they also felt was plagued with inefficiencies and waste with respect to time, effort, and material (Womack et al., 1990). Unable to achieve the levels of vertical integration or large standardized production volumes in Western automotive assembly plants, Toyota chose instead to adapt Ford's continuous-flow principles to provide greater production flexibility and product variety. Toyota accomplished this by integrating its assembly plants with a local network of parts suppliers to reduce inventory requirements and enable a "Just-in-Time" (or JIT) delivery model, whereby only the parts and components needed on the factory floor at a particular time were manufactured and delivered to the production line (Krafcik, 1988).

By eschewing the "Just-in-Case" inventory philosophy used in most Western plants, TPS drastically improved plant level efficiencies by eliminating supply stockpiles. Toyota also developed a technique to change sheet metal stamping dies in a fraction of the time, allowing them to produce metal parts in much smaller lot sizes and instead produce a greater variety of products along a single production line (Krafcik, 1988). Toyota's production system inspired the idea of lean manufacturing, which keeps inventory levels to a minimum to reduce costs and allows quality problems to be quickly identified and resolved. A lean management strategy can offer higher efficiency returns but can involve much higher levels of risk because of the potential of having to shut down a production line in the event that a problem is detected.

Nieuwenhuis and Wells (2007) insisted that both Ford and Budd were equally responsible for defining the structure of contemporary automotive manufacturing. They believed that "while Fordism was possible without Budd, 'Toyotism' refines Fordism within Budd technology" (p. 204), suggesting that the lean production practices popularized by TPS would have been irrelevant without the context of Budd's all-steel body (Nieuwenhuis & Well, 2007). The all-steel body is responsible for the highly automated system of mass production that characterizes modern assembly plants and the high capital investment associated with automotive manufacturing, both of which contribute to the economic processes of "lock-in" and "path-dependence".

1.5 Path-Dependence in Technological Regimes

A socio-technical regime refers to the embedded societal and economic conventions that shape the existing set of dominant technologies and support organizations and institutions, collectively known as a socio-technical system (Bakker, Maat, & van Wee, 2014). Consequently, this combination of formal (i.e., organizational and institutional), and informal (i.e., societal) rules results in the frequent exclusion of new and radical innovations that may disrupt the existing structure. Innovation within an established socio-technical regime is often limited to incremental improvements that either reinforce or reproduce the existing paradigm in a process known as path-dependence. Changing a regime involves large scale and often long-term systemic changes to prevailing technological, organizational, and institutional designs. These changes must occur simultaneously for a transition to occur and to overcome opposition from the dominant regime and its incumbents (Bakker et al., 2014).

Studies on the adoption and diffusion of innovation often incorrectly assume that superior attributes and features are responsible for determining the success or failure of a technology (Briggs, Webb, & Wilson, 2015). However, external factors are routinely responsible for the failure of superior innovations, allowing a sub-optimal system to persist. Conversely, such pressures can also prompt a transition when they conflict with the existing regime. Successful innovation requires financial support from either the public or private sector to fund their development, to gain public support and understanding, and to establish a favourable political and regulatory environment to establish a viable niche (Bakker et al., 2014). A niche represents a relatively limited number of consumers who are willing to pay a premium for innovation and is often an environment where technology can be nurtured, incubated, and improved before it is introduced to the masses and must compete with the incumbent regime (Bakker et al., 2014; Steinhibler, Wells & Thankappan, 2013).

Many factors can influence a consumer's rationale for choosing a particular product over any number of alternatives. However, some studies have found the presence of social and institutional factors relating to customs, circumstances, and habitual behaviours can outweigh attribute considerations and rational choice (Briggs et al., 2015). Another important determinant is the influence that governments and industry have on a user's social environment and choice selection (Briggs et al., 2015). The presence of external factors unrelated to product characteristics suggests that consumer choice is often imperfect and irrational which, under processes of lock-in and path-dependence, allow for the sustained selection of sub-optimal alternatives (Briggs et al., 2015). Path-dependency results when previous decisions constrain decisions in the present (Wells & Nieuwenhuis, 2012). These economic concepts relate well to the development of the American transport system and its selection of the ICE and the private automobile alongside the continued growth of its related industries and a proportional reduction in the use of public transportation (Briggs et al., 2015).

These economic processes speak to the difficulty in challenging an established regime, which is no truer than in the automotive industry given that it has relied on the same core technologies and production processes for nearly a century. At the same time however, these processes reinforce the need for radical innovation in the automotive industry, given that sustainability improvements within the current socio-technical paradigm will be incremental at best.

1.6 Contextualizing the Canadian Automotive Industry

Domestic automotive manufacturing in Canada began in the early 1900s, motivated by high tariffs on imported vehicles and favourable tariffs on Canadian-made products exported to the British Commonwealth (Holmes, 2014). An end to the British Empire’s trade preference in the early 1960s crippled the Canadian branch plants that had been established to take advantage of these export markets. Canada’s domestic demand could not sustain the existing production capacity of the established branch plants, which could no longer capture scale efficiencies (Holmes, 2014). As such, there was little incentive to invest in Canada’s automotive industry, until 1965 when the Canada-US Auto Pact (i.e., the Automotive Products Trade Agreement of 1965) resurrected the industry by integrating the Canadian and US markets and removing automotive trade barriers (Crane, 2017).

Two Canadian-written annexes contained within the agreement stipulated minimum levels of Canadian value added and a production/sales-ratio ensuring that for each vehicle sold in Canada there was at least one vehicle built in Canada. The US market accounted for over 80% of the vehicles assembled in Canada throughout the 1980s. The Canada-US Free Trade Agreement (FTA) of 1989 maintained the aforementioned Canadian safeguards contained within the Auto Pact. However, Canada agreed to stop offering duty-remission[3] incentives to attract Japanese Transplants to Canada for export to the US. The provisions of the Auto Pact became less important in determining automotive investments when Mexico was added to the North American Free Trade Agreement (NAFTA) of 1994. These renewed ties between the US and Canada maintained barrier free automotive trade and supported the continued prosperity of the

[3] Duty-remission is a duty exemption scheme that allowed companies to offset duties on imported automotive parts by increasing exports of Canadian-made automotive parts (Crane, 2017).

Canadian automotive industry, which was operating far above the production/sales-ratio and minimum value added requirements stipulated in the Auto Pact (Crane, 2017).

The automotive industry in Canada is highly concentrated in the province of Ontario along a narrow corridor extending between the cities of Windsor and Oshawa. The Canadian automotive manufacturing footprint is an extension of the manufacturing cluster in the Northeastern part of the US, predominantly scattered between New York, Michigan, Ohio, Indiana, Illinois, and Wisconsin (Holmes, 2014). The heyday of Canadian automobile manufacturing was in 1999 when it became the fourth largest automotive producing nation in the world, assembling 3.06 million vehicles. Accordingly, the country’s automotive trade balance peaked in 1999 at which time the total value of exported automotive goods exceeded the total value of imported automotive goods by $14.6 billion (Holmes, 2015). The flow of automotive trade between the US and Canada peaked the same year with exports and imports valued at $44.76 billion and $19.52 billion, respectively. The success of the Canadian auto industry during this period was rooted—for the most part—in the vibrancy of the US consumer market and its demand for Canadian-built vehicle models, particularly light-duty trucks, SUVs, and minivans (Holmes, 2014). Other important success factors at the time were Canada’s lower dollar and subsequently lower cost of labour, and the lower cost of employee health care benefits (Holmes, 2014).

Unfortunately, the favourable conditions that fostered this growth did not persist. By 2000, Canada’s automotive industry began a steady decline (Holmes, 2014). Between 2002 and 2008, four assembly plants were shuttered and Canada’s automotive trade balance—for the first time in decades—turned negative in 2007 (Holmes, 2014; Holmes, 2015). Factors contributing to this decline were the end of the Auto Pact in 2001; declining market share by North America’s domestic manufactures as a result of increased automotive imports from Japan, Europe, and South Korea; and the loss of Canada’s labour advantage due to a higher Canadian dollar and concessions by the American automotive labour unions—specifically the United Automobile Workers (UAW; Holmes, 2014). The remaining Auto Pact provisions that were carried over into the Canada-US FTA and NAFTA, later on, continued to upset vehicle and part manufactures in Japan and the European Union (EU). A complaint brought forth by these jurisdictions to the

World Trade Organization (WTO) successfully ended the Auto Pact, and its remaining Canadian safeguards (Crane, 2017).

The Canadian government had chosen not to appeal the WTO decision as all three members of the pact (GM, Ford, and Chrysler) were all operating well above the minimum mandated production and value-added safeguards intended to protect Canada’s manufacturing footprint (Mordue & Sweeney 2017). The industry’s strong performance in Canada (driven mainly by high productivity, publically funded health care, and a lower currency relative to the US) meant that the Auto Pact’s Canadian safeguards had not been enforced for almost two decades. As a result, its dismissal was mostly seen as inconsequential and the long-term impacts of its cancelation were easily overlooked (Mordue and Sweeney, 2017).

Furthermore, the Canadian Government’s unwillingness to offer any additional subsidies following the cancellation of the Auto Pact may have contributed to the decision by GM, Ford, and Chrysler to each close one of their Canadian plants within a three-year period following the cancellation of the Auto Pact. Dozens of large automotive parts facilities also abandoned their Canadian operations in the aftermath, many of which were American owned companies that had located in Canada originally to satisfy the value added safeguard (Sweeney & Mordue, 2017). Additionally, although Honda and Toyota operated transplants in Canada, Canadian suppliers remained heavily dependent on the “Big Three” (i.e., GM, Ford, and Chrysler), which were steadily losing market share to foreign vehicle imports and transplants, making them particularly vulnerable to the plant closures following the WTO decision in 2001 (Holmes, 2014).

Economic uncertainty following the 2008 financial crisis triggered a pronounced decline in 2009: American automobile sales decreased by 38% (13% in Canada), automotive production fell by 46% (42% in Canada), and US employment in the automotive sector was reduced by 32% when compared to 2007 levels (Holmes, 2014). General Motors and Chrysler entered accelerated bankruptcy restructuring south of the border and were required by the conditions of their government bailout to cut labour costs—to the greatest extent possible—to match that of Toyota and Honda’s non-unionized workforces. Although neither company entered bankruptcy protection in Canada, they both accepted financial assistance from the federal government, which was concerned with the potential loss of its manufacturing footprint in the aftermath of the crisis.

As part of their bailout package, both companies agreed to keep 16% of their North American manufacturing operations in Canada through until 2016.

Following the recession, Canada's recovery has been less robust than the recovery in the US and even less so than Mexico's, where there was rather rapid growth following the financial crisis (Homes, 2014). The three NAFTA signatories compete with one another for automotive investments. However, the health of the US consumer market tends to have a significant influence on the manufacturing industries in Canada and in Mexico. Mexican-built vehicles and automotive parts flow into the US and—to a lesser extent—into Canada. By 2012, automotive production in Canada and the US once again matched the pre-recession levels of 2007. However, employment growth in Canada was negligible and the country's rank among the world's largest auto-producing nations fell to the 11^{th} spot (Holmes, 2014). Comparatively, employment in the automotive sector nearly doubled in Mexico between 2007 and 2012, making it the 5th largest automotive parts exporter in the world (Holmes, 2014).

Canada is increasingly unable to compete with Mexico for new automotive investments due to their steep wage advantage. Canada's negative trade balance with Mexico grew to $9.12 billion in 2014 as more automakers made investments in Mexico, including high margin luxury VMs (Holmes, 2015). In 2014, BMW announced its plans to invest $1 billion in Mexico, where the construction of two new assembly plants was already ongoing: One by Audi, and the other jointly by Nissan and Mercedes-Benz at a cost of $1.3 and $1.4 billion, respectively. Such announcements were particularly concerning given that Mexico historically attracted smaller, low-margin vehicles as opposed to higher-margin vehicles from premium brands. Furthermore, during the first quarter of 2015 Toyota announced that it would be shifting production of its Corolla model (which had been built at its Cambridge, ON plant since the 1980s) out of Canada by 2019 to a new plant in Mexico[4] at a cost of $1 billion (Evans, 2015). Production at the Cambridge plant will continue with an unspecified model that is said to be a larger and more expensive vehicle with deeper profit margins (Evans, 2015). Mexico is an increasingly attractive destination for the assembly of subcompact and compact vehicles due to its lower profit margins and therefore benefits most from Mexico's labour advantage (Holmes, 2015).

[4] More recently, Toyota announced that Corolla production would be moving to a new US plant built jointly with Mazda Motor Corporation (CBC, 2017a).

1.7 Thesis Objectives and Research Question

In an effort to contribute to existing research that has attempted to develop a possible theoretical view of what a sustainable automotive industry could look like in the future, this thesis will explore: (1) The combined synergies between innovative process technology to revolutionize contemporary vehicle design; (2) Innovative product technology to replace traditional propulsions technologies; and (3) New innovative business models, and consider what a possible transition towards MFR could look like and how long it might take. Specifically, this thesis will attempt to answer whether the joint impacts of additive manufacturing (AM) and EM could enable a more sustainable form of automotive production and distribution known as MFR, and if the circumstances in Canada are favourable to facilitate such a transition.

The Canadian market is an ideal candidate for an analysis of possible future outcomes for a sustainable automotive industry for two primary reasons. First, the future of the Canadian automotive manufacturing industry is growing ever more uncertain as the amount of automotive investments allocated here have been significantly smaller relative to other auto-producing regions in North America, namely the Southern US and Mexico. Second, several Canadian provinces (British Columbia, Ontario, and Québec) have attempted to position themselves at the leading edge of EV policy development and EV adoption. Both of these factors suggest that the Canadian automobile industry is poised for change, and that a focus on innovation and sustainability could lead to the competitive advantage Canada needs to maintain the prosperity of this important industry.

Essentially, this research aims to outline a potential technological pathway for MFR and suggest potential policy implications for both industry and government that should be considered to enable a more sustainable and economically viable automotive ecosystem. The practicality and feasibility of these policy prescriptions will be demonstrated with a detailed review of three empirical examples of the proposed technologies and business concepts being used by innovative new entrants’ attempts to disrupt the status quo in the automotive industry.

1.8 Thesis Contents

This next chapter will describe the major economic and environmental challenges that are facing the automotive industry and have together led to the emerging doubt regarding the future sustainability of the current mass production paradigm. The current strategies and measures being used by the industry to mitigate the effects of these challenges will also be outlined within the Chapter Two. The third chapter will outline the emerging scientific field of industrial ecology (IE), which formed the theoretical basis for the MFR model and the ecological modernization of the automotive ecosystems, including previous applications and criticisms. Chapter Four will describe how IE can be used to improve the sustainability of the automotive industry by expanding the IE's theoretical framework with specific ecological concepts. The MFR model will also be detailed within this chapter.

Chapter Five will introduce the process of AM and argue how it could be used to enable a transition towards MFR. Chapter Six consists of a detailed review of the literature on EM and will form the basis for the discussion in Chapter Seven regarding the need for business model innovation to overcome lock-in and path-dependence in the current socio-technical regime and enhance the synergies between the proposed technological innovations and the MFR model. By stifling innovation, these economic processes could prevent a transition towards a more sustainable system that is based on a different set of core technologies and processes. The eighth chapter will discuss three case studies illustrating the use of the proposed technologies (i.e., AM and EM) to disrupt the status quo in the automotive industry and potentially drive change in the fundamental design of contemporary automobiles, and how they are made, sold, and used, to demonstrate the feasibility of the proposed product and process innovations in stimulating sustainable system innovation in the form of MFR in the automotive industry.

Chapter Nine contains a discussion of a potential methodology that could be used in future research to approximate the impacts of and a timeline for system innovation in the automotive industry and considered whether the circumstances in Canada favour a transition to MFR by hypothesizing potential intermediate steps and outcomes of a transition following the proposed technological pathway. Chapter Ten will conclude the thesis with a synthesis of major findings and research contributions, and areas of potential future research.

Chapter 2 Driving Change in the Automotive Industry

2.1 Regulating the Car and its Environmental Impacts

Pollution controls on carbon monoxide (CO), nitrogen oxides (NO_x), un-burned hydrocarbons (HC), and particulate matter (PM) have received the most attention from regulators over the second half of the 20th century, out of concern for human health rather than out of concern for the planet or the environment (Nieuwenhuis, 2014). California was the first jurisdiction to begin imposing regulations on tailpipe emissions when it established the Air Resource Board (ARB) in 1967. Having more private vehicle registrations than any other state and boasting some of the nation's worst air quality, California became a leader in environmental regulation, setting a global benchmark for air quality standards and tailpipe emissions.

Vehicle emissions are determined by running a vehicle's engine through a standardized test cycle that is intended to simulate the conditions of a typical trip (Nieuwenhuis, 2014). Test cycles fluctuate by region, contributing to variations in regulatory standards which can increase costs and complexity for VMs. Due to the size and influence of the US automotive market and because California's regulations are among the most stringent in the world, the ARB's regulations have acted as a template for other jurisdictions who have adopted them in part or in full. Maximum allowable emissions in Japan, for instance, closely resemble those in the US given that the US is a significant export market for Japanese OEMs (Nieuwenhuis, 2014).

Examples of technological innovations stemming directly from environmental regulation are catalytic converters and engine management systems to reduce tailpipe emissions (Nieuwenhuis, 2014). Catalytic converters, for instance, are effective at reducing the concentration of HC, CO, NO_x, and other pollutants from engine exhaust fumes. Despite their efficacy, catalytic converters required significant cooperation between the automotive and fuel industries to achieve mass adoption. In the early 1970s, prior to this technology, gasoline was enriched with lead (Pb) because it boosted the performance of spark-ignited engines by preventing self-ignition (i.e., engine knock) by increasing the octane rating of gasoline (Lovei, 1998). Lead additives were also effective at lubricating exhaust valves, allowing lower-grade metals to be used for their construction.

However, leaded gasoline reduced the effectiveness of catalytic converters, potentially causing damage to them if lead was deposited on the catalytic material, blocking it from the exhaust gases. The impetus for removing lead additives from gasoline in the US was the use of catalytic converters as well as public outcry over the health impacts of airborne lead exposure (Lovei, 1998). Lead is a cumulative neurotoxin that impairs brain development in children and can cause elevated blood pressure in adults leading to an increase in negative health outcomes. The phasing-out of lead additives from gasoline was considered at the time to be a complex issue that required political commitment, cross-sectional cooperation, government incentives, as well as the support and understanding of the public (Lovei, 1998). The widespread introduction of catalytic converters on new vehicles required gasoline refineries to invest in modernizing their equipment to produce gasoline with higher octane ratings and allow for the removal of lead additives. Once a supply of unleaded gasoline was available, automakers could commit to installing catalytic converters on all new vehicles as well as using hardened engine valve seats to operate without the lubricating effects provided by leaded gasoline.

Catalytic converters are only one example of the tremendous effort that can be required to achieve emission reductions in the automotive industry. For this reason, regulatory frameworks often outline incremental targets that require the gradual reduction of toxic emissions within a predetermined timeframe. Overtime, as more regulatory standards are introduced, the cost of manufacturing is likely to increase. The cost of technological improvements, necessary to satisfy increasingly rigorous environmental standards, are likely to become more expensive over time and require greater research and development (R&D) investments by OEMs (KPMG Int., 2010).

2.1.1 The Cost of Environmental Regulation

Automakers and industry executives have resisted nearly every attempt by policy makers to regulate any aspect of motor vehicles, including safety, emissions control, or energy use (Sperling, 2004). The industry's assertion was always that greater regulation would lead to economic hardship. Research from the Institute for Transportation Studies at the University of California, Davis found that the industry's claim about stringent, technology forcing regulations might not have been justified or reasonable. It was found that although policies relating to motor vehicle safety, emissions reduction, and increased fuel economy between 1967 and 2001 had indeed contributed to the price increase of new vehicles during that period, the proportion relative to the total price increase was modest. The total cost of quality improvements and other cost factors (including regulation) between average new vehicle prices in 1967 and 2001 was determined to be $12,480 (Sperling, 2004). Based upon the same government data, Ward's Automotive Yearbook estimated that regulatory improvements accounted for about $4,020 (or one-third of the price increase of new vehicles between 1967 and 2001). Based on his detailed review, Sperling (2004) believed this was an overestimation and set the cost of regulation for vehicles in 2001 at $2,500 (one-fifth of the price increase of new vehicles between 1967 and 2001)—of which only $1,000 was said to be the result of emissions regulations while the rest was attributable to improvements in vehicle safety. The majority ($9,980) of the price increase during the study period was due to improvements in reliability, durability, fit-and-finish, and performance. It was also noted that improvements in emission control systems and fuel efficiency during the study period would have occurred regardless, even in the absence of regulation, due to shifting consumer demand because of changing social views and perceptions (Sperling, 2004). For instance, the safety features and equipment that are available on modern vehicles far outpace regulatory requirements because of the significance consumer's attribute to vehicle safety.

Despite industry push back, regulations have been pivotal in achieving dramatic improvements in vehicle emissions—modern automobiles emit 90 to 99% less toxic air pollutants than vehicles pre-dating government regulation (Sperling et al., 2004). Another indication of the need for ongoing regulation is the lack of improvement to vehicle fuel efficiency following 1985, when more stringent CAFE standards took effect. It is not that further improvements in efficiency have not been achieved since 1985, but rather that those improvements have been counterbalanced by increases in vehicle size and weight, performance and acceleration, and an increase in energy intensive vehicle features and options such as all-wheel drive and air conditioning. This research suggests that although regulators should be sensitive to the potential economic impacts of new regulations, it is not true that past attempts to regulate the car and its environmental impacts have led to economic hardship in the automotive industry.

2.1.2 The Cost of Resisting Regulation

A recent and highly publicized example of a covert attempt to circumvent emissions regulations, likely to avoid added costs in manufacturing and R&D, was Volkswagen's (VW) 2015 "dieselgate" scandal. As Europe's largest automaker, VW is highly influenced by consumer preferences in its home market. Since the 1990s, roughly half of new cars sold in Europe have been equipped with a diesel engine (Voelcker, 2015). As competing automakers (e.g., Toyota, GM, and Ford) began to introduce hybrid-electric powertrains to comply with US fuel efficiency standards, VW opted instead to pursue greater fuel efficiency exclusively with what it called "clean diesels". Adding to the complexity of the situation was the divergence that occurred in 2008 between the emission standards in place for diesel engines in the US and Europe. The US adopted much stricter rules in its tiered regulatory framework for diesel engines while the equivalent European standards remained unchanged, maintaining its existing so-called "Euro 5" standards. Volkswagen believed not only that diesel technology was intrinsically more cost efficient than hybrid technology, but that it offered superior performance with better driving dynamics and acceleration (Voelcker, 2015).

Volkswagen did not offer an electrified powertrain in the US until 2013 when it launched its low volume Touareg hybrid SUV. Volkswagen's hesitation and resistance to pursuing alternative powertrain technologies meant that it had no choice but to rely on its diesel engine technology to meet mandatory US fuel efficiency standards for its vehicle fleet. Another potential factor contributing to VW's decision to cheat on US emissions tests was the added costs associated with technologies used for emissions control in diesel engines. Other VMs offering diesel engines as an option chose to equip them with selective catalytic reduction (SCR), a second catalytic converter that uses a urea injection to convert NO_x into nitrogen and carbon dioxide (CO_2). Volkswagen chose to equip only select diesel models with this technology, possibly to avoid further increases to the already significant price premium for its diesel engines. As a volume brand, VW caters to a more price sensitive consumer than other German brands, including its own luxury brand Audi as well as BWM and Mercedes-Benz, who can more easily command a higher price premium for their diesel engine equipped models (Voelcker, 2015). Volkswagen's diesel vehicles also had an important reputation to maintain, being fun to drive and having superior acceleration and fuel economy than their gasoline counterparts. Abiding by the new, stricter US emissions standards for diesel engines would have likely jeopardized this marketable reputation by requiring a decrease in both acceleration and fuel efficiency (Voelcker, 2015). Tuning a diesel engine to release greater amounts of NO_x actually improves its overall fuel efficiency. Volkswagen was clearly invested in maintaining the brand image and market share it had created for its clean diesel technology.

In September, 2015 the US Environmental Protection Agency (EPA) issued a notice of violation to the VW group[5] for its 2.0 litre four cylinder diesel engines sold between model year (MY) 2009 and MY 2016 (approximately 550,000 vehicles in the US and 11 million vehicles worldwide) that were equipped with "defeat devices"—as defined by the Clean Air Act—to circumvent EPA emission standards for NO_x (Bartlett, Naranjo, & Plungis, 2016). A second notice of violation was issued to VW Group, Porsche AG, and Porsche Group of America in November of 2015 regarding its 3.0 litre V6 diesel engines (approx. 85,000 vehicles in the US) which were also equipped with defeat devices (Bartlet et al., 2016). The malicious devices made use of sophisticated software capable of distinguishing between real world driving conditions and test cycle conditions. The device allowed the offending vehicles to pass emissions tests by limiting the amount of NO_x released during testing situations while alternatively allowing vehicles to emit as much as 40 times the permissible limit of NO_x during real world driving (Bartlett et al., 2016). This scandal illustrates the perils of not actively pursuing innovative technologies that will allow OEMs to achieve increasingly stringent emission and fuel efficiency regulations that are in place in the US and increasingly around the world.

While high excise duties on fuel in Europe and Japan helped generate market demand for smaller, more fuel efficient vehicles, the US government had to take a legislative approach to decreasing its reliance on foreign oil in the wake of the 1973-1974 fuel crisis triggered by an embargo on gasoline exports from Arab oil producing nations to the United States (UCS, n.d.a). Corporate Average Fuel Economy standards were introduced in 1975 and set a maximum allowable fleet-average fuel economy for all passenger cars sold by a VM during a given year (Nieuwenhuis, 2014). Pre-regulation fleet-average fuel economy was in the range of 15 miles per gallon (mpg). The sales-weighted CAFE standards required automakers to achieve an average fuel economy of 18 mpg by 1978 and 27.5 mpg by 1985 (Sperling et al., 2004). Minivans, pickup trucks and SUVs were given a separate, less stringent target. If automakers failed to

[5] Comprising of Volkswagen AG, Audi AG, and Volkswagen Group of America

achieve the fuel economy standard a fine had to be paid. Automakers performing better than the required average could sell credits—calculated in the same way as the fines—to offending automakers that did not meet the required targets. This scheme provides automakers with a financial incentive to improve their fleet-average fuel economy voluntarily beyond what is required by the regulatory standard (Nieuwenhuis, 2014). The Energy Independence and Security Act of 2007 finally increased the aging CAFE standard form 27.5 mpg to 35 mpg (14.8 km/l) by MY 2020 (KPMG Int., 2010). Growing concerns over the human health effects of air pollution, market demand for more fuel efficient vehicles as a result of rising fuel prices and concerns over oil dependence, and greater awareness of the greenhouse gas (GHG) effects of CO_2 emissions triggered the current era of social regulation on the car which began in the 1960s.

2.2 Market Challenges and Economic Pressures

While the global automotive industry can be analyzed at various micro-level scales, including individual years, regions, or manufacturers, the aim of this section is to highlight long-term trends and challenges that have perpetuated in the industry. Overall, the industry can exhibit significant variation in terms of annual sales volumes or net profits since external economic shocks (e.g., various oil crises and the global recession in 2008) which can have a dramatic impact on the success of the industry. Aside from this inherent vulnerability, the automotive industry faces some fundamental challenges that are associated with its core technological competencies and its dominant business model. When viewed along timescales of several decades, it becomes evident that the global automotive industry's prevailing economic and environmental performance cannot be sustained indefinitely and—due to greater political and social pressure—will have to change how it operates and how it generates value in the future to become more environmentally and economically sustainable (Wells & Nieuwenhuis, 2004; Wells & Orsato, 2004). It is becoming increasingly likely that the automotive industry will undergo a major paradigmatic shift as traditional automotive stakeholders attempt to remain competitive while contemplating a more sustainable future for mobility that is characterized by disruptive technologies and business models (Goa, Kaas, Mohr, & Wee, 2016; Wells & Orsato, 2004). The specifics of this sustainable future are still unknown, but can be explored theoretically in the field of Industrial Ecology (IE). Before exploring a theoretical alternative for a more sustainable future, the current issues and challenges facing the industry must be understood. The changing regulatory environment in which the industry is embedded was discussed above; below, the market and economic challenges affecting the industry will be discussed.

2.2.1 The First Waves of Globalization in the Automotive Industry

Globalization in the automotive industry seems inherently unavoidable as automakers strive for greater economies of scale in production. Globalization also leads to greater competition, as demonstrated by the experience of North American automakers. The post-war period in North America was characterized by a seemingly insatiable demand for new vehicles (Howleg, 2008). Established North American automakers experienced nearly uninhibited growth until the first oil crisis: a two-year embargo starting in 1973 increased consumer demand for small, fuel efficient economy cars in response to the quadrupling of US fuel prices (Sperling et al., 2004). North American automakers were ill equipped to handle this sudden shift in market demand, creating a gap in the market for more efficient and economical vehicles. This provided an opportunity for Japanese producers to enter the US market—the world's largest automotive market at the time—successfully with vehicles that, at least initially, undercut the established American producers on both efficiency and price (Holweg, 2008).

Although American automakers could not have been expected to predict an external shock like a spike in oil prices following a geopolitical dispute, higher gasoline prices alone were not what allowed Japanese automakers to climb to the top of the American market even after gasoline prices had stabilized. Japanese manufacturing plants worked quite differently than traditional western automotive production by maximizing efficiencies through a lean production system, which enabled greater production flexibility and improved quality. Japanese imports were competitive not only because of their more modest price, but because of their superior quality. The inflexibility of the traditional American-style production system meant that domestic automakers could not respond to the oil crisis as quickly, causing them to lose market share to their Japanese rivals (Holweg, 2008).

The competitive threat of Japanese import vehicles in the US was eventually met with a growing political discourse regarding possible protectionist policies and trade barriers to protect domestic employment and the US economy (Howleg, 2008). Japanese producers reacted swiftly to these threats by "transplanting" production of some of their best-selling vehicles in the North American market to the US. By the 1980s, Japanese VMs were highly competitive and were quickly moving upmarket to compete in nearly all market segments. This gave South Korea's burgeoning motor industry a similar opportunity to expand its market share and break into the North American market, initially with small economical cars appealing to the most price sensitive consumers. Lower labour costs within emerging markets often provide manufactures with an initial competitive advantage when importing products into mature markets with higher labour costs, such as the US and Canada (Howleg, 2008).

Today, South Korea's indigenous automakers now compete on a level playing field with North American, European, and Japanese producers in terms of build quality, performance, and feature content. Hyundai Motor Company purchased a controlling stake in South Korea's second largest auto company, KIA Motors, to form the Hyundai Motor Group. As they began their shift upmarket, they too expanded their production footprint and began assembling certain models within the US to supply domestic demand. The Hyundai Motor Group recently spun its Genesis nameplate into its own premium brand—in the same way Honda moved into the premium/luxury segment with the introduction of Acura in North America, which was also replicated by Toyota and Nissan with Lexus and Infinity, respectively. Given that history has already repeated itself, it seems likely that the next wave of import competition in North America will be led by newly established Chinese manufactures as they initially compete at the low end of the market in pursuit of greater economies of scale (Holweg, 2008).

2.2.2 Globalization through Regionalization and Consolidation

The geography of globalization in the automotive industry is surprisingly complex and asymmetrical (Stanford, 2010). The automotive industry is dominated by a handful of globally oriented OEMs, selling vehicles in all major markets and increasingly planning their technological, production, and marketing operations around a globalized strategy. However, given the automotive sector's disproportionate economic importance, resulting from its strong economic linkages with other industrial sectors and the employment spin-off from both upstream and downstream supply chains, the industry demonstrates significant regional tendencies as well (Stanford, 2010). Among the world's leading global OEMs, there remains a propensity to build vehicles near the location where they will be sold. Both economic and political influences contribute to the regionalization of investment and production in the automobile industry. For example, trans-oceanic transportation costs can add as much as ten percent to the cost of final production vehicles (Stanford, 2010). Furthermore, the industry's adoption of a JIT inventory strategy—a hallmark of TPS—is not amenable to global component sourcing because of the tightly managed logistics that are required by lean production (Stanford, 2010). The JIT production strategy has conversely encouraged the agglomeration of parts suppliers around automotive assembly plants. Perhaps this shift could be interpreted as the industry's best approximation of localization or a localized strategy insofar as it lowers logistics costs by reducing the distance between where vehicles are manufactured and where they are eventually sold while simultaneously maintaining the same fundamental business model and production technologies.

Political influences contributing to increased regionalization include the avoidance of protectionist policies such as tariffs and import quotas. Globalization in the automotive sector therefore presents itself in various forms including globally integrated management and marketing strategies, standardized global vehicle platforms, and foreign direct investment (FDI) for the construction of assembly plants in foreign markets (Stanford, 2010). In an attempt to expand their global presence, leading OEMs have collaborated with indigenous automakers in foreign markets. These partnerships can take on various forms. While some involve a complete take-over of one OEM by another, some involve the purchase or trade of minority equity rights to facilitate the sharing of resources and knowledge in such areas as technology, engineering, and marketing (Stanford, 2010). This global consolidation of OEMs was quite common throughout the 1990s and resulted in several smaller vehicle manufactures (e.g., Volvo, Saab, Daewoo, MG, and Jaguar Land Rover) ceasing to exist on their own and being integrated into the operation of much larger globalized OEMs—granting them access to new markets and increasing their presence within the world's most dominant markets (Stanford, 2010).

2.2.3 Changing Patterns of Globalization

The aftermath of the 2009 global financial crisis brought to light the complexity and asymmetry that exists within the automotive sector's pattern of globalization (Stanford, 2010). The crisis affected regions around the world quite differently as a result. Prior to the rise of automobile industries in emerging economies of the BRIC (Brazil, Russia, India, and China), the industry was regionally concentrated within the developed world (Stanford, 2010). The three dominant markets hosting the largest globally oriented OEMs were North America (the US and

Canada), Western Europe, and East Asia (Japan and South Korea). However, the vitality and financial success of the OEMs indigenous to these regions has been very different given uneven patterns of international trade and investment (Stanford, 2010).

One element contributing to the differing response of these regions to the financial crisis is the variation in their apparent net exports, the difference in domestic production and domestic sales. This summary metric indicates each region's level of participation in global automotive trade and, whether or not, the overall production level of each region is proportional to its own domestic demand. Before the global financial crisis, Japan and South Korea produced more than twice as many vehicles as they consumed domestically, meaning the region had a large, positive apparent net export (Stanford, 2010). The region benefits from largely closed domestic markets, meaning indigenous OEMs control around 90% of the domestic market share. This dominance in their home market is what initially allowed South Asian OEMs to pursue a more globalized strategy through exports and FDI, focused primarily in North America. South Asian OEMs invested significantly in the North American market between 1996 and 2010; they now account for close to 40% of North American vehicle production through their 25 assembly plants (Stanford, 2010). Like automotive trade, FDI in South Asian markets is asymmetrical in nature with nearly all FDI flowing outwards with hardly any FDI from non-indigenous OEMs flowing into the region (Stanford, 2010).

Production and trade performance in North America is quite different. North American-based OEMs are suffering a reduction in domestic market share because of an increasing dependence on net automotive imports and growing inbound FDI (Stanford, 2010). Before the financial crisis, net imports of new vehicles accounted for nearly one-fifth of domestic vehicles sales. The crisis itself exacerbated the situation as North American producers suffered larger production cuts than other automakers, allowing the net import of foreign vehicles to increase (Stanford, 2010). On the other hand, outgoing automotive trade from North America is small and offsets only a fraction of the region's total automotive imports, resulting in a negative automotive trade balance. Already in a fragile state, North American OEMs suffered disproportionately from the impacts of the financial crisis.

The uneven geography of automotive globalization, with asymmetries in both automotive trade and FDI, combined with an already shrinking domestic demand made North America's Big

Three highly vulnerable to the effects of the financial crisis (Stanford, 2010). The Big Three suffered crippling net losses between 2005 and 2008, totaling more than USD $100 billion—representing nearly the entire equity base of all three companies (Stanford, 2010).

The effects of globalization on European OEMs lies somewhere between the East Asian and North American experience. European-based OEMs have maintained a relatively stable dominance over their home market, controlling about two-thirds of the market share for new vehicles. Imports of finished vehicles into Europe, coming predominantly from East Asia are balanced with vehicle exports, mainly to North America but to other world regions as well (Stanford, 2010). Although Western Europe as a whole has been successful in maintaining a relatively stable trade balance, there have been changes—more recently—in the location of new automotive investments and production capacity within the region. With the expansion of the EU in 2004 to include former Communist countries, Central and Eastern Europe became an attractive region for export-oriented automotive investments, due to their lower labour costs, to supply the larger automotive markets of Western European countries. In fact, automotive production in these former Communist countries doubled between 2004 and 2008 (Stanford, 2010).

2.2.4 Vehicle Manufacturers in Emerging Markets Pursue Globalization

It should also be noted that European VMs have not been immune to the trend of global consolidation, which sees smaller independent firms overtaken by larger global players with foreign ownership. This has resulted in the disappearance of indigenous OEMs in secondary automotive producing countries in Europe. In the UK for instance, British Leyland Motor Corporation, which formed after the merger of British Motor Holding[6] and Leyland Motor Corporation[7] was downsized when it sold the Rover Group to the BMW Group in 1994, which included the Land Rover and Mini brands (Automotive News, 2015). However, after consistent losses, BMW broke up the Rover Group in 2000 selling Land Rover to the Ford Motor Company and auctioning off MG (which had been a part of Morris under British Leyland). The liquidation of MG Rover in 2005 marked the end of a British-owned OEM; Rover's technology and

[6] Grew out of the acquisition of Morris Motors, Aston Motor Company, and Jaguar Cars (Britannica, 2015).
[7] Formed from the merger of Leyland Motors and the Rover Company.

production equipment, as well as the MG name, were purchased by China's state-owned SAIC Motor Corporation (Automotive News, 2015).

Both previously under the ownership of British Leyland, Jaguar and Land Rover were reunited as a subsidiary of Ford in 2000 when it purchased Land Rover. Ford had purchased Jaguar in 1990 (Britannica, 2015). However, in an effort to raise capital and ensure its own survival during the financial crisis, Ford sold Jaguar Land Rover (including the luxury Range Rover marque) in 2008 to India's multinational conglomerate Tata Group (Bajaj, 2012). Tata Motors appears to have accomplished an unprecedented feat, as a company from a developing country to, successfully, turn around a struggling western automotive company. Redesigned Range Rover vehicles have been positively received by critics and consumers, benefiting from growth in the popular luxury SUV class, while Jaguar's recently debuted, first ever SUV has received similar praise. Tata successfully introduced the brands into the Chinese market where luxury car sales have surpassed those in the US (Bajaj, 2012). Jaguar Land Rover has been enjoying record sales and sustained growth, even expanding its manufacturing footprint into emerging markets outside of China, including Brazil and Slovakia.

Similarly, Swedish VM Volvo was purchased by Ford in 1999 as part of its Premier Automotive Group, which included Aston Martin and Jaguar Land Rover. Volvo was the last of Ford's Premier Automotive brands to be sold off during the financial crisis to raise capital and avoid bankruptcy protection. The sale of Volvo was finalized in 2010 to China's Geely Automotive Holdings Ltd for significantly less than what Ford had initially paid to acquire the brand. The sale represented the largest acquisition of a foreign automaker by a Chinese company and reflected the growing influence of the Chinese automotive market, which had surpassed that of the US to be the largest in the world just one year prior (Yan & Leung, 2010). As Tata is attempting to do with Jaguar Land Rover, Geely plans to expand the Volvo Car brand into the Chinese market by investing heavily in new models and new assembly plants in China (The Economist, 2014). The company also has plans to export Chinese made Volvo vehicles into the US, which would represent the first Chinese made vehicle to be exported to the US. The introduction of Chinese built Volvo cars in the US could help pave the way for Geely to expand its namesake brand in the US, representing a fourth wave of automotive globalization into the US (The Economist, 2014).

2.2.5 The Start of a Regional Strategy and the Potential Perils of Globalization

As suggested by the above narrative, globalization within the automotive industry is highly complex and asymmetrical, even within the traditional dominant automotive producing regions of North America, Western Europe, and East Asia. The desire to be global is also balanced by a significant tendency to regionalize automotive production as automakers look to gain market share and overcome potential economic and political barriers. This tendency is illustrated by the presence of Japanese and South Korean transplants in North America (Stanford, 2010). Regional differences in the cost of labour are more significant at the low end of the market, where profit margins tend to be much lower and where competitive advantage is often achieved through price, given the higher price sensitivity of consumers in the economy segment (Holweg, 2008). Initially, import producers from Japan and South Korea leveraged their cost advantage through reduced labour costs and success in their home markets to compete with domestic OEMs in North America and Western Europe (Holweg, 2008; Stanford, 2010). Through the pursuit of a globalized strategy and the use of FDI to regionalize some of their production in North America, Japanese and Korean automakers now compete on an even playing field with traditionally dominant OEMs, achieving a 17% and 37% market share in Western Europe and North America, respectively (Holweg, 2008). A superior manufacturing strategy and the inability—at least initially—for Western VMs to match their levels of productivity and quality control allowed these producers to be competitive in foreign markets (Holweg, 2008). Indigenous OEMs in these regions initially resisted the transition to "leaner" manufacturing methods, pursuing instead the prevailing industry mantra of the 1990s that size (i.e., production volume) and global market coverage would ensure survival (Holweg, 2008). Industry alliances were pursued by several automakers looking to maximize on the advantages of scale, including BMW's aforementioned venture with Rover and GM's alliance with Fiat in 2000.

However, industry alliances based only in the pursuit of scale were misguided and often set up for failure. An example of a successful industry alliance based not only on scale but also on strong complementarity in term of capabilities and market coverage is French automaker Renault's merger with Japanese automaker Nissan (Holweg, 2008). Nissan's strong manufacturing capabilities in lean production complemented Renault's expertise in design. Similarly, Nissan's largest market share remains in Asia and North America while Renault is well represented in both Europe and South America. Their strong complementarity and global market reach produced a fruitful merger while limiting redundancies and overlap (Holweg, 2008). Successful OEMs of the future will be those who are able to find new ways of creating value and creating beneficial partnerships with new, previously distinct stakeholders (IBM, 2004).

However, scale alone does not ensure survival. An automaker will not be guaranteed success based solely on size and scale (IBM, 2004). Yet, the phrase "too big to fail" is often used with reference to the automotive industry. For instance, proponents of the government bail out of the North American car-industry during the 2008 financial crisis often relied on this argument as justification. The thought was that certain large corporations are simply too important to go bankrupt because the resulting unemployment would be devastating for the economy and be politically unacceptable, and the impact on financial markets and economic growth would be too great (Schuman, 2008). Hence, the rationale for government loans to stave off the bankruptcy of a private firm. Conversely, the orchestrated collapse of South Korea's influential Daewoo Group in 1999 in the wake of the Asian financial crisis demonstrated that actually letting a large conglomerate fail as a result of its own mismanagement and poor performance could potentially benefit the economy over the medium- to long-term. Daewoo, South Korea's fourth largest industrial conglomerate, became too much of a burden after an ill-conceived global expansion (including of its automotive division) left the company saddled with debt. As with Daewoo, GM and Chrysler proved in 2008 that size alone does not ensure one's survival.

2.3 A New Era of Regionalization: Shifting Production and Future Growth

The geography of global automotive production is undergoing a dramatic shift. Traditionally dominant auto-producing regions, namely the US, Western Europe and Japan (collectively referred to as the TRIAD) are enduring a net loss of production capacity as older plants are shut down while new investments are increasingly being directed away from traditional markets in favour of emerging markets, where a rapidly growing middle class has set its sights on motorization and car ownership (Holweg, 2008; KPMG Int., 2013). In 1970 for instance, these established automotive manufacturing regions accounted for 91% of the world's total automotive production (Holweg, 2008, p. 22). At the time, the US, and western Europe especially, had major net positive automotive trade balances while both Japan's domestic and export production were increasing rapidly. The aforementioned shift in global automotive production geography was well underway throughout the 1990s. By 2004, the TRIAD's share of global automotive production had fallen to about 70%. Between 1970 and 2004, the total number of automotive assembly plants worldwide grew by 263, from 197 plants in 1970 to 460 plants in 2004 (Holweg, 2008, p. 22) The TRIAD only accounted for 44% of the new assembly plants during this period, clear evidence of a shift in the geography of global automotive production and investment.

The majority of these new automotive manufacturing plants were built in emerging markets which—because of significant growth in their domestic demand—could now justify the large capital investments required to build full-scale automotive assembly plants. At the time, Latin America was a key emerging market attracting new automotive investments. Not only was domestic demand increasing in the region but, due to its lower labour cost, close proximity to the US, and new free trade agreements, it was also well suited to building smaller economical cars with modest profit margins for export to the US (Holweg, 2008). Between 1980 and 2000, vehicle production in Argentina, Brazil, and Mexico nearly doubled, reaching a combined output of nearly 4 million units by the year 2000 (Holweg, 2008). This pattern of shifting production capacity towards emerging markets and away from traditional industrial nations does not appear to be slowing down as automakers bet their future success on the rising automotive demand in Brazil, Russia, India, and especially China who's dramatic economic growth has been the most impactful (KPMG Int., 2013). Collectively, these four emerging markets are referred to as the BRIC, given that they are at a similar stage of economic development and it is thought that they could form a powerful economic bloc in the future.

Global consulting firm KPMG conducts an annual survey of global automotive executives to uncover the most pressing trends and issues facing the future of the industry. For three years straight (2013-2015) the number one key trend in the industry as ranked by automotive executives was growth in emerging markets (KPMG, 2017). Executives in both TRIAD and BRIC nations agreed that growth in emerging markets was an important industry trend (KMPG Int., 2013). Specifically, executives in both the TRIAD and the BRIC have their sights set primarily on China followed by India and then Brazil and Russia in third and fourth place, respectively (KPMG, 2014).

The surveys have also revealed that consumer demand and expectations in emerging markets increasingly resemble those in more developed markets. Consumers in emerging BRIC markets are increasingly favouring larger and more upscale vehicles, including SUVs and multi-purpose vehicles (MPVs), midsize sedans, minivans, and pickup trucks, as a way of demonstrating their newfound wealth (KPMG Int., 2013). In China for instance, SUVs are the fastest growing vehicle segment, experiencing dramatic year-over-year growth. Female consumers in China have especially embraced SUVs, with their popularity attributed to their utility, safety, and style (KPMG Int., 2013). North American and European automakers alike are eager to cash in on this tremendous growth opportunity. Ford introduced four new SUV models in the Chinese market before its target of 2013 and Fiat Chrysler Automobiles (FCA) announced it was working alongside Chinese automaker Guangzhou Automobile Group Co. to work out a plan to manufacture all of its Jeep nameplates in China (KMPG Int., 2013). The luxury SUV segment is also being embraced in China. Porsche's Cayenne SUV has been popular with Chinese consumers while Lamborghini chose the Beijing motor-show to debut its first ever SUV concept, the Urus. As of 2009, China became both the largest automotive market surpassing the US and the largest automotive producer surpassing Japan (Stanford, 2010). With such fast growing demand in emerging markets such as China, it is understandable why the industry is paying attention and has been shifting its investment patterns away from traditional markets, where demand has become relatively stagnant for some time.

The primary reason for the reorganization of the world's automotive manufacturing base is the anticipated shift in the geography of automotive demand. The majority of the projected growth in automotive demand is expected to occur primarily within emerging economies, like the BRIC, where the consumer class is rapidly expanding (Holweg, 2008). Demand in traditional markets on the other hand has stagnated for many years or has grown at a much slower rate. As a result of both economic and political forces, OEMs are choosing to distribute their manufacturing operations in hopes of capitalizing on the expected growth in automotive demand in emerging economies. As previously mentioned, employment spin-off effects provide the automotive industry with a disproportionate economic and political influence making it politically advantageous for governments to encourage and even subsidize the construction of new assembly plants. This shift in production capacity bodes well for countries desperately trying to develop, but is worrisome for established auto-producing countries, such as Canada, who face the threat of plant closures and the associated loss of employment. To an extent, this shift represents a localization of the automotive industry: new investments in production capacity are being directed towards emerging markets where a new appetite for motorization and car ownership is resulting in higher demand (Holweg, 2008). The demand in emerging markets is now sufficiently high to justify the large capital investment required to build full-scale automotive assembly plants (Holweg, 2008).

For instance, production capacity for passenger vehicles was virtually non-existent in China prior to 1980. Just over two decades later, in 2004, China was producing 2.32 million vehicles for its domestic market (Holweg, 2008, p. 22). To date, China's fledging automotive sector has been entirely self-contained with no significant automotive trade moving into or out of the country (Stanford, 2010). Growth in China's automotive demand has so far been balanced by increases in domestic production. Chinese based OEMs have not yet been successful in globalizing their operations into markets like North America and Western Europe. China has instead become an important market for established OEMs to expand their global footprint and cash in on the countries increasing demand. In fact, 90% of the vehicles manufactured in China in 2004 were produced by a company involved in a joint venture with an established global OEM (Holweg, 2008).

The young automotive industries of other quickly emerging markets have also exhibited a relatively self-contained growth pattern, not yet posing an imminent threat to the TRIAD. Despite managing small net export surpluses, the large majority of the automotive production that is taking place in both India and Brazil is used to satisfy their growing domestic demand (Stanford, 2010). The public perception—especially in developed nations threatened by plant closures—of the relationship between automotive globalization and labour cost, tends to be that automotive manufacturing concentrates in jurisdictions with the lowest labour costs. While there is evidence of this occurring regionally within North America and within Europe, where free trade agreements have facilitated some migration to lower cost jurisdictions, this cannot be said of the industry's expansion and migration into China, Brazil, and India, whose growth is driven primarily by increases in domestic production rather than growth in automotive exports (Stanford, 2010).

However, this is not to say that OEMs in the BRIC do not intend to globalize their operations. They have been developing their own growth plans to increase international market share and were found to be more likely than their peers in the TRIAD to raise their investments in all regions of the world. While automakers in the TRIAD have focused their regional expansion primarily in BRIC nations, indigenous BRIC automakers have increased their investments not only in the BRIC but also into younger emerging markets in South East Asia, Africa, Eastern Europe, and South America more so than their TRIAD counterparts have. Due to stiff competition and a wide range of existing consumer options, Western Europe and North America remain predominantly off-limits for BRIC-based OEMs. Rather, their largest growth opportunities tend to be in South East Asia, including Thailand, Indonesia, and Malaysia. These markets are attractive not only for their growth in domestic demand but also for their close proximity to larger markets like China and India (KPMG Int., 2013). Eastern Europe and South America are the next two most promising growth opportunities for BRIC automakers and could act as launch pads for a future expansion into more established markets like Westerns Europe and North America respectively.

The bold step of entering into mature markets will most likely take place from hubs in lower cost regions. For instance, China's Zhejiang Geely Holding Group Co Ltd has expanded its automotive production into the Ukraine and Belarus. Similarly, in South America, both Mexico and Brazil have developed strong trade agreements with China and other BRIC nations making them attractive locations for a future expansion into the US (KPMG Int., 2014). Along with tax incentives from the country's Inovar-Auto program, which began in 2012 and for which preliminary data has shown promising results in terms of increasing the number and quality of R&D investments related to the automotive supply chain, local and state governments in Brazil are trying to lure foreign automotive investors with a variety of incentives (de Mello, Marx, and Motta, 2016). Brazil is now tied with Mexico as a first choice for export oriented automotive production to the US. With the BRIC nations having experienced enormous growth over the last number of years, automotive executives anticipate that the next wave of growth is likely to take place in other parts of the world including: Thailand, South Africa, Indonesia, Turkey, Argentina, and Saudi Arabia, with the countries ranked in order of the percentage of survey respondents that rated the country as the next emerging market in KPMG's Global Automotive Executive Survey 2016.

2.3.1 Market Saturation and Overcapacity

Overcapacity is a challenge that has afflicted the automotive industry for decades as demand in traditional markets has stagnated or, in some cases, even declined. The overcapacity problem has been perpetuated through time because of the industry's systemic failure to adjust its production capacity to levels of consumer demand. The huge capital investment required to build an assembly plant and the desire to maintain economies of scale in production contribute to the lack of flexibility that perpetuates the overcapacity problem. Asymmetries with respect to capacity adjustments also contributes to overcapacity by making it far easier to build additional capacity than it is to remove or reduce it (Holweg, 2008). Given the direct and indirect employment benefits associated with automotive industry, governments often encourage and even subsidize the new assembly plants. However, when existing plants are underutilized due to lower demand, the decision to reduced or removed capacity quickly becomes political as governments attempt to maintain the numerous social and economic benefits associated with their existing manufacturing footprint.

Global overcapacity was estimated to have been as high as 20 million units, which results in large inventories of new, unsold vehicles. It is standard for automakers in most markets to have inventories of 1.5 to 2 months (Holweg, 2008). Sales incentives such as discounting, high trade-in pricing, and free upgrading are used to combat growing inventories and to maintain market share and economies of scale in production (Holweg, 2008). Perpetual discounting can further erode the already low profit margins of volume automakers. Furthermore, capital tied up in large vehicle inventories cannot be invested in other areas of the business such as R&D, innovation, and product development.

The high production volumes necessitated by the Ford-Budd mass production system are no longer relevant in highly competitive mature markets, where demand has generally stagnated and where product variety and customization are increasingly valued. About half of respondents in KPMG's 2013 annual Automotive Executive Survey agreed that there is a risk of overcapacity in mature markets: Japan, Germany, the US, South Korea, Spain, and France. Two thirds of executives surveyed in 2014 ranked the risk of overcapacity as either "high" or "very high" in Germany, France, the US, and Japan with only slightly less risk in Spain and South Korea. Although industry executives appear to be aware of issues related to overcapacity, it does not appear as though they agree on a solution. There is considerable variation between the solutions deemed more appropriate by executives from different countries. The solution ranked most frequently as “most effective” by the surveyed executives was “industry consolidation/joint ventures/strategic alliances” at 25% of respondents (KPMG Int., 2013). “Increased vehicle exports” and “government incentives” were tied for second place, each with 19% support; while “OEM incentives” received 17% support (KPMG Int., 2013). “Production cutbacks”, “raising brand profiles”, and “increased contract manufacturing” received the least support from automakers, with only French auto executives particularly favouring cutbacks in production (KPMG Int., 2013).

Regionalization in the automotive industry is exacerbating issues of overcapacity; new assembly facilities are being built in emerging markets more quickly than they are being shut down in traditional markets. Existing capacity in mature markets is often difficult to reduce because of strong political pressure to maintain manufacturing employment. Overcapacity in the US has diminished recently—with some automakers citing local under capacity—because of rebounding sales following the 2008-2009 recession, which created pent-up demand (KPMG Int., 2014). Automotive sales in the US hit another record high in 2016, narrowly beating the record set in 2015, due in large part to strong demand for light-duty trucks including SUVs and CUVs. The shift away from sedans is not expected to ease anytime soon—good news for OEMs with a wide selection of light-duty trucks, which often command larger profit margins because of their size and price. Similarly, Canada achieved its fourth consecutive sales record in 2016 (Keenan, 2017). As the only remaining growth spot in the TRIAD, auto sales in the US and Canada are expected to cool off slightly in 2017 due to the continued slow demand for traditional vehicle segments (e.g., large and midsize sedans).

2.3.2 Product Differentiation

Established global automakers have been forced to adapt to the challenges presented by saturated demand in mature markets: intensifying competition, changing consumer expectations, and reduced brand loyalty (Güttner & Sommer-Dittrich, 2008). Slow or stagnate growth in the TRIAD, which will likely remain a pivotal market for global OEMs, means that the only way automakers will be able to increase their market share in the future will be at the expense of their competitors by offering superior products with more available and higher quality equipment options and features. This implies that "not more, but qualitatively better and more expensive vehicles" will be sold in the future to ensure competitiveness (Güttner & Sommer-Dittrich, 2008, p. 59). Given the abundance of choice in the automotive market—with most vehicles now exhibiting similar levels of quality, functionality, and performance—automakers have no choice but to offer a wide range of distinctive and differentiated products to satisfy the unique needs of consumers living in different markets around the world (Branstad, Williams, & Rodewig, 1999). Regionalization has also contributed to the rising importance of product differentiation as automakers operate in more and more foreign markets—where regulatory differences and locale taste preferences require vehicles to be regionally distinctive (Güttner & Sommer-Dittrich, 2008).

Automakers have dealt with increased competition and changes in consumer demand by expanding their product portfolio and by increasing the variety of available features, options, and equipment. Developing products that uniquely combine both functional and expressive, or emotional, attributes in order to appeal to enough consumers to ensure a decent ROI is a complex and expensive task (Branstad, et al., 1999). Between 1988 and 2008, the number of equipment options available on new vehicles sold in Europe tripled, while the range of available models quintupled (Güttner & Sommer-Dittrich, 2008). Sophisticated consumers in mature markets desire personalized products that cater to the specific needs and wants of their individual lifestyle as opposed to standardized products designed and engineered for global appeal (IBM, 2004). Increasingly, consumers in emerging markets are demanding the same level of quality, performance, and features as consumers in the TRIAD (KPMG Int., 2013).

Creating an array of products that are both distinctive and emotionally engaging is not only a challenge but carries significant risk. Many automakers have chosen to differentiate their products by focusing on niche vehicles and crossovers as opposed to traditional vehicle segments (namely sedans) in an attempt to combine both functional and emotional appeal in a new and unique package (Branstad et al., 1999). Emotional appeal is often achieved through innovative designs and styling cues that can differentiate a model from its competitors. Increasing variety in the automotive market has resulted in the implosion of traditional vehicle segments as they become ever more fragmented with finer and more precise definitions. In 1990, the European car market was made up of 187 different models. By 2003, model variety had increased to 315 different models (Holweg, 2008). Entirely new vehicle segments were created due to the appeal of personalization and differentiation, including Pony Cars (e.g., Ford Mustang & Chevy Camaro); Sports Sedans (e.g., BWM M5 & Cadillac CTS-V); Luxury SUVs (e.g., Jeep Grand Cherokee & Cadillac Escalade); and Hot hatches (e.g., Volkswagen Golf GTI & Ford Focus RS).

The development of niche vehicles with more radical designs and bolder styling can be a risky endeavour for automakers, especially if they fail to achieve the desired combination of emotional and functional appeal. The cost of designing and engineering a new model and retooling an assembly line for its manufacture is costly, sometimes reaching into the billions of dollars (Branstad et al., 1999). If, however, a product proves successful, the benefits can be significant, providing generous ROI—so long as it is able to maintain its distinctiveness among its competitors (Holweg, 2008).

A recent vehicle segment that has been highly successful and remains one of the fastest growing segments in North American is the crossover utility vehicles (CUVs). The shift to larger and more expensive CUVs offering larger profit margins was a major reason why American OEMs on the brink of collapse were able to return to profitability so quickly after the financial crisis. Crossover vehicles combine desirable features found in SUVs, such as a higher ride height, available all-wheel drive, and a rear liftgate, with the same passenger compartments, driving dynamics, and creature comforts expected form a traditional sedan—combining style and functionality (Holweg, 2008). Crossovers borrow their underpinnings—and therefore their handling and ride quality—from their sedan counterparts, which contributes to their added popularity. The major trade-offs of this unibody construction are reduced off-roading and hauling capabilities as compared to traditional SUVs, which use a body on frame design (DeMuro, 2015).

Offering a more extensive product range can increase costs by reducing supply chain performance with the introduction of dis-economies of scale that can increase component costs, lead times, and inventory requirements (Schaffer & Schleich, 2008). On the other hand, increased product variety can lead to greater market share and larger volumes overall. Lower sales volumes of individual models could erode economies of scale, reducing an automaker’s ability to recuperate the high development costs involved in engineering and designing a new product (Holweg, 2008). However, automakers have been actively combatting this by increasing platform and powertrain sharing between various models in their portfolio and even between brands owned by the same parent company. The challenge when pursuing product differentiation is twofold: (1) developing a deep understanding of consumer needs and wants—to reduce the number of product flops, attempts ill-received by the market—and (2) reducing both the amount of time and money required to develop new products by improving the design and engineering processes involved in product development (Branstad et al., 1999).

Accompanying the trend of increasing model variety is a shortening of the traditional vehicle life cycle, defined here as the length of time a particular model stays on the market before receiving significant changes. Vehicles are receiving more frequent and more extensive “mid-cycle refreshes” before they are scheduled to be fully redesigned, which is also occurring more frequently for a variety of reasons. One reason for this is the level of competition that now exists in nearly all vehicle segments. Automakers are trying to gain a competitive advantage by improving their product lineup more frequently in order to make older designs appear stale. This constant product improvement does come at a price however. Nissan’s Chief of Product Strategy said in a media interview that his company spent three to four times more than usual to refresh its two-bestselling sedans to incorporate the newest in safety technology and upgrade the infotainment system, among other things (Wernle, 2016). Along with innovations in safety and connectivity, tightening fuel economy standards and consumer demand for greater efficiency can also prompt automakers to introduce changes to their powertrains prematurely. One consultant estimates that today’s product facelifts can run as high as $100 to $200 million. Automakers need to give consumers a reason to visit their showroom or upgrade into a new vehicle, perhaps following the end of a lease agreement, which can result in customers visiting showrooms far more frequently, and often an extensive product refresh can be enough to boost a model’s sales (Wernle, 2016).

Although consumers are increasingly demanding the newest and most advanced technology and safety features in their vehicles, the trend towards more frequent and extensive product updates could potentially have a negative effect on the industry’s long-term sustainability. It could be argued that this trend is an example of the controversial business strategy known as planned obsolescence—the process by which a product becomes obsolete or, at least, undesirable before the end of its useable life cycle. The purpose of planned obsolescence is to encourage consumers to upgrade or prematurely replace a product before the end of its useful life cycle (Guiltinan, 2009). The ethical issues surrounding this practice are often debated given its negative environmental impacts with respect to resource efficiency and the economic burden it places on consumers to always purchase the latest products (Guiltinan, 2009). The replacement strategy employed in the automotive industry relies mostly on technological obsolescence, which is often considered voluntary as there is no practical reason why the product would no longer be useful, rather than on physical obsolescence, which render a product unusable or in need of repair (Guiltinan, 2009). A vehicle is said to be beyond economic repair when the cost of repairing the vehicle exceed its current market value, and should instead be replaced. In general, the industry tends to favour replacement rather than retrofitting, repairing, or component upgrading, all of which would increase the industry's environmental sustainability.

The first documented application of planned obsolescence was in the automotive industry, introduced by Alfred P. Sloan—head of GM—in the mid-1920s (Kitman, 2009). He introduced the notion of annual model changes and the idea that this year's model ought to be better, faster, and more exciting than last year's, to encourage upgrading and replacement buying (Kitman, 2009). Planned obsolescence was essential to GM's success and its ability to overtake Ford as the world's leading automaker—which has been cited as the first example of fashion positioning being favoured over durability positioning in the consumer durables market (Kitman, 2009; Slade, 2006). Ford's competitive strategy was to increase efficiencies and drive down prices to increase sales while Sloan's approach emphasized superior performance and styling—to convince consumers to purchase a newer product that they essentially did not need (Kitman, 2009).

Planned obsolescence is used in part to remain competitive within a market that has become increasingly crowded with new models and options and that has faced perpetual overcapacity because of saturated demand. The rate of technological innovation is also exacerbating the need for frequent product updates, as is the need to appeal to a new generation of consumers who increasingly view vehicles as a fashion accessory, akin to their smartphones. Updating aging models mid-way through their typical life cycle is now standard practice and is often used to sustain consumer interest and demand, which tends to evolve much faster than standard model development timelines. General Motors implemented this strategy during its post-bankruptcy restructuring to become more competitive (Kranz, 2012). It was believed that regular styling changes and product enhancements would be more cost effective than marketing aging vehicle designs with steep sales incentives—a custom that had become common at GM. With fewer sub-brands in its portfolio following its restructuring, GM now had the resources to update its vehicles more frequently (about every three years). The plan also allowed them to be swifter with respect to technological advancements and regulatory changes (Kranz, 2012).

2.3.3 Marketing and Distribution

A forthcoming challenge for VMs will be their outdated method of selling and distributing vehicles—a key pillar in the established industry paradigm—through a network of franchised dealerships. This approach limits the level of OEM engagement at the consumer interface leaving the task of forging strong, positive consumer relationships on marketing alone. Intense competition and market saturation are increasingly forcing automakers to search for new ways to generate and capture value throughout vehicle life cycles. Automotive manufacturers have traditionally shied away from downstream revenue capture, participating instead in the assembly and distribution phases of vehicle life cycles (Branstad et al., 1999). Today, automakers are attempting to capture a greater proportion of the total value chain of their vehicles by either "following the car" or "following the consumer" (Branstad et al., 1999). The former approach relates to increasing their involvement in the various transactions that take place after a vehicle is sold during its useful life cycle. The latter approach relates to cultivating and fostering stronger relationships with consumers in the hope of participating in future transactions with them over their buying lifetime. The current reliance on franchised dealerships could make it more difficult for OEMs to pursue either of these strategies directly.

The current distribution model transfers manufacturers' returns to intermediaries, creating a gap between them and their customers. This reduces the amount of influence OEMs have over their consumer interface and reduces the effectiveness of costly marketing campaigns (Branstad et al., 1999). Further distancing manufacturers from their consumers is the consolidation of franchised dealerships. Across the US, large dealership networks—hosting multiple competing brands—are working to generate their own brand image and strengthen their control over the consumer interface. AutoNation is the largest such dealer network in the US and is publicly traded on the New York Stock Exchange. The company oversees 290 dealerships spanning 15 states and nearly every automotive brand. By surrendering the consumer interface to car dealerships, OEMs are further removed from downstream transactions in the value chain, relegating them to mere metalsmiths in the eyes of consumers. A constellation of dealerships, such as AutoNation, is concerned with selling as many vehicles as possible; the make of the individual vehicles in a sense becomes irrelevant, unless an OEM is successful in maintaining a coveted brand image.

Furthermore, the success and popularity of leasing programs has also put the needs of OEMs at odds with those of their franchisees. Automakers have an interest in maintaining high residual values for their vehicles while dealers prefer to buy low and sell high when it comes to the sale of used or off-lease vehicles. Vehicle manufacturers have made significant strides with improvements to vehicle quality and reliability. The same can generally not be said about improvements to the consumer interface, i.e., improving the experience of buying and owning a vehicle (Branstad et al., 1999). A major challenge for the future will be cultivating a better understanding of consumer needs and increasing the level of direct contact automakers have with their customers, to better attract service and retain them amid intense competition from both established and emerging VMs (Branstad et al., 1999). Direct sales strategies in North America are currently offered by Tesla Motors and South Korea's new luxury brand Genesis.

2.4 Vehicle Manufacturers' Strategic Response

2.4.1 Industry Consolidation and Cooperation

Global VMs have a history of consolidating their operations. The motivation for consolidation is to share development costs, streamline distribution networks, eliminate excess production capacity, and to negotiate lower prices with suppliers based on higher volumes (The Economist, 2015). Acquisitions are sometimes targeted to gain access to new or underdeveloped markets or to inherit a particular technology (Hoelz, Collins, & Roehm, 2009). In other cases, multiple acquisitions are used to rationalize capacity and become the dominate player in a particular niche market. Consolidation could increase in the future as the emerging markets in China and India become more prominent and their indigenous brands attempt to expend their business internationally. The recent acquisition of Western firms by Geely and Tata are early signs of this future trend. Recent comments by FCA's CEO Sergio Marchionne grabbed headlines as the automotive executive brazenly promoted his desire to see his company merge with GM, who was quick to rebuff the proposition. Marchionne has publically rebuked the automotive industry for the enormous amount of capital it requires to develop new models, suggesting that up to half of these costs are squandered in the development of proprietary technologies rarely distinguishable to consumers (The Economist, 2015). In his view, automakers should collaborate in developing fuel-saving innovations instead of each automaker pursuing their own costly development program.

The partnership that began in 1999 between Renault and Nissan is now viewed as an industry benchmark (Hoelz et al., 2009). Similar partnerships are likely to emerge in the future, as industry pressures require automakers to seek further cost reduction strategies. Their strategic alliance was used to reduce development and R&D costs for new vehicles using shared architectures and to have greater purchasing power when negotiating with suppliers thanks to increased volumes (Hoelz et al., 2009). One reason for the success of this alliance was its hesitation to fully integrate both companies. Common synergies between the French and Japanese automakers ensured the alliance was mutually beneficial while their decision to maintain independent management teams preserved the existing culture of each company (Welch, 2015). Mergers are often met with heavy resistance when one party tries to assimilate the other and impose its own practices. As previously mentioned, the two brands generally operate in different markets, limiting the amount of direct competition between them.

Indeed, there are several examples of passed mergers and ill-conceived alliances that were unsuccessful in achieving the desired level of cost savings and subsequently failed. Examples including the merger between Renault and Volvo; the merger between Daimler and Chrysler, and their subsequent alliance with Mitsubishi; the alliance between Ford and Fiat; BMW's acquisition of Rover, and Ford's Premier Automotive Group with Volvo, Jaguar, Land Rover, and Aston Martin (The Economist, 2015; Welch, 2015). Although consolidation is often pursued in an effort to generate greater economies of scale, reduce costs, and increase profits, these outcomes are not a guarantee. For instance, it took 21 years for Renault-Nissan to achieved part sharing synergies equivalent to those at GM, with about 70% of their vehicles sharing common parts and components (Welch, 2009). Similarly, any future large merger between equals would take many years before the initial costs of the merger were recovered through joint efficiencies and cost savings (Economist, 2015). In terms of the effect of scale on generating higher profits margins, as measured by earnings before interest, taxes, depreciation and amortization (EBITDA), both Nissan and Renault generated margins that were lower than those achieved by Honda, who sells about half as many cars. Furthermore, GM sells even more cars than Renault-Nissan and achieves even lower margins, proving that scale alone does not ensure higher profit margins (Welch, 2015).

2.4.2 Increased Outsourcing and Supplier Responsibility

Vehicle modules as defined by automotive OEMs are sub-assemblies, or groups of physically adjacent components, that can be tested and assembled outside of the main assembly line in order to reduce complexity and save time during final assembly (Sako & Warburton, 1999). The outsourcing of complete modules to automotive suppliers increased as Western automakers attempted to interpret and implement the principles of lean manufacturing in their operations. The result has been a drastic increase in the responsibility of suppliers to design and manufacture complete modules that can be easily assembled by OEMs. Automotive suppliers are now manufacturing over 80% of the parts and components that go into a vehicle, meaning the focus of contemporary OEMs is on vehicle assembly, distribution, and marketing rather than manufacturing (Kallstrom, 2015).

This dramatic shift in responsibilities encouraged consolidation among the supply base as suppliers attempted to gain the relevant knowledge and expertise needed to assemble component modules. A new tier of automotive supplier has emerged due to the increased outsourcing by OEMs. Traditionally, Tier 1 suppliers delivered parts directly to VMs. Consolidation has increasingly displaced these suppliers with larger “Tier 0.5” suppliers that act as system integrators. These new, larger suppliers source parts from many different suppliers to build a complete sub-assembly or module that can be easily assembled onto several vehicle models along an assembly line. As OEMs increasingly downgraded responsibilities onto their supply base, suppliers were forced to consolidate to acquire a wider range of competencies to fulfill this new role. As suppliers’ activities account for a greater proportion of the value in vehicle manufacturing, they may, in the future, establish direct channels and touch points with consumers to participate in downstream value capture—threatening the positioning of traditional OEMs at the head of the supply chain (Gao, Kaas, Mohr, & Wee, 2016).

2.4.3 Platform and Component Sharing

Another common strategy used by VMs to cut costs is "platform sharing". The strategy involves the use of the same platform or chassis to underpin numerous models within a single brand or across brands with the same parent company. Platform and component sharing is not a recent phenomenon. In the 1960s, GM used common platforms and powertrains for several different models across its brand stable including Pontiac, Buick, Chevrolet, and Oldsmobile (Csere, 2003). Back then, however, models sharing multiple mechanical components tended to also share common sheet metal with little more than a differentiated front and rear end to distinguish them. The practice was often disparagingly referred to as "badge engineering" (Csere, 2003). No longer is this the case. Consumers today are often unaware of the amount of shared components between vehicles in the showroom and on the road. Platform sharing has become ubiquitous in the industry as it allows the high capital costs of engineering and tooling up an assembly line for a new model to be amortized over a number of different models achieving greater economies of scale.

Nowadays, the terminology used by most automakers is "shared architecture" rather than platform sharing. The term architecture generally refers to derivatives of a single platform, meaning it may have been stretched or shrunk to accommodate a different body style (Sabatini, 2014). This means contemporary platform sharing cannot only span multiple models and brands but different vehicle segments as well. Not only are CUVs based on the same architecture as sedans, but also compact sedans can now share a version of a platform used in a larger and more expensive premium product like a mid- or full-sized sedan.

Volkswagen AG may become a pioneer in the automotive industry if its planned mega-platform strategy is successful. The plan, announced in 2012, involves the use of only four modular architectures to be used across all of the company's 12 brands, including both mass market and niche brands, including Bentley and Lamborghini (Henry, 2015). Internally referred to as the MQB platform[8], VW's first modular architecture is by far receiving the most attention. The MQB platform is anticipated to underpin all of Volkswagen AG's front-wheel drive vehicles across all its brands, accounting for nearly 80% of the vehicles the company assembles. The platform will also be used globally, in assembly plants in Europe, North and South America,

[8] MQB refers to a German acronym meaning "modular transverse matrix".

China, and South Africa. Historically, vehicles produced in emerging markets would use an older less advanced platform to cut costs but with consumer demand in these markets now rivaling those in more established markets, it makes sense for VMs to use a common global platform (Henry, 2015).

The degree of "plug-and-play modularity, flexibility and parts commonality" found in the MQB platform far exceeds that of major VW competitors and means the company could soon be building up to 40 models across several of its mass-market brands using a single flexible architecture (Frost, Cremer, & Lienert, 2013). Some industry analysts have likened VW's MQB architecture with previous influential innovations like Ford's moving assembly line, GM's ladder of brands, and the Toyota production system (TPS). Although it is potentially revolutionary, the MQB architecture has reportedly cost the automaker $70 billion to implement. However, estimates suggest that the successful adoption of the MQB platform could generate cost savings of as much as $19 billion annually by 2019 (Henry, 2015). When VW unveiled the plan, it said its MQB concept could save up to 20% on component costs while also reducing the time to market of new models by 20%. With the large investment involved, only time will tell if VW will achieve its predicted ROI. The competitive advantage however could be short lived with GM announcing similar plans to consolidate its many platforms into only four by 2025 and Toyota announcing what it calls its Toyota New Global Architecture (or TNGA) which is also akin to VW's strategy.

An unintended consequence of platform and component sharing and the consolidation of suppliers is a huge increase in the number of vehicles affected by quality and safety recalls. Take the recent Takata air bag recall, which has been described by the National Highway Traffic Safety Administration (NHTSA) as "the largest and most complex safety recall in US history" (Barlett, 2017). The Recall spans 19 different automakers and vehicles from MY 2002 all the way to MY 2015, totaling more than 42 million vehicles in the US alone (Barlett, 2017).

2.5 Conclusion

This chapter gave a synopsis of the major challenges facing the contemporary global automotive industry. Those challenges were split into two broad categories: environmental and economic pressures. Environmental challenges stem primarily from increasingly stringent regulations on exhaust emissions and fuel economy. However, there is also growing demand among environmentally conscious consumers and those concerned with the cost of fuel. The auto industry generally opposes any form of regulation out of fear of economic hardship, but as dieselgate has shown, there can also be high costs associated with resisting technological change and regulation.

The second broad category of industry challenges was economic pressures, which included the joint—and sometimes opposing forces—of globalization and regionalization as well as the changing geography of global vehicle production and demand. Perpetual overcapacity has long been a challenge for more mature markets, and is now being exacerbated by rapid growth in certain emerging markets. Consumers are also demanding greater variety and differentiation in their products, presenting a challenge for automakers and fueling planned obsolescence to maintain high levels of demand.

Given the plethora of challenges, OEMs have had to develop new strategies to secure their market share and maintain their profitability performance. Vehicle manufacturers have increasingly looked at each other for support, either through consolidation to achieve greater economies of scale or increasing cooperation to share development costs. Furthermore, OEMs are relying much more on their suppliers, by outsourcing full vehicle modules, thereby spurring consolidation among their supply base. Finally, VMs have developed common vehicle architectures to increase part and component sharing between models and brands to cut costs and remain globally competitive.

Before presenting a sustainable alternative to the paradigm that was described in the above chapter, the following chapter will review an emerging scientific field that will serve as the theoretical basis for a proposed alternative model that could be used to achieve greater sustainability in the automotive industry in the future.

Chapter 3 Achieving Sustainability in Industrial Systems

3.1 A Historical Perspective of what is Natural

In the first chapter of his 2014 book *Sustainable Automobility: Understanding the Car as a Natural System* Paul Nieuwenhuis explored the origins of the widespread belief—especially in the West—that humankind is somehow separate from and distinct from the rest of nature. The agricultural revolution was cited as a possible source for this perception of nature. Civilization's use of modern agriculture has instilled it with a sense of great control and power over nature, which could have contributed to the notion that humans and nature are somehow estranged from one another (Challenger, 2011). The onset of agriculture also marked the beginning of humankind's influence on the climate. It was at this time that concentrations of CO_2 and methane (CH_4) in the atmosphere started to trend upwards away from their expected values as a result of land clearing/deforestation for cultivation, cattle rearing, and wet rice cultivation—a significant source of CH_4 gas (Ruddiman, 2005). Of course, this departure from the norm was much less severe than the impeding industrial revolution that caused a much more pronounced increase in atmospheric concentrations of GHGs.

Religion was cited as another possible source contributing to society's perceived alienation from and superiority over nature. Many religions, some of which developed alongside the agricultural revolution, perpetuate the belief that humankind is distinct from or has power and authority over nature (Nieuwenhuis, 2014). Christianity, for instance, suggests that the rest of creation exists primarily for the benefit of humans—God's intellectual creatures (Nieuwenhuis, 2014). Aside from humankind's exploitation of nature, Christianity also casts humans as environmental stewards, benevolent protectors of the rest of creation. Although the idea of environmental stewardship and conservation are often viewed positively, they should not be confused with environmental sustainability for they maintain the idea that nature is separate from humankind and its impacts (Nieuwenhuis, 2014).

Implicit in the notions of stewardship and conservationism is the idea that humans are free to choose when and where conservation is practiced to suit their own needs. Conservation is typically restricted to particular sites that are deemed worthy of such efforts (e.g., conservation areas and national/provincial parks). The reality of conservationism is, therefore, the protection of ecosystem services from which humans have been deriving a benefit to ensure humankind's ability to continue to live and thrive on earth (Nieuwenhuis, 2014). This bias towards protecting the needs of humankind over those of nature was also evident in the above discussion regarding regulating the car and its environmental impacts. Regulations affecting the car and its use were derived not from an intrinsic desire to protect the environment but rather out of concern for the adverse effects cars had been having on human health.

Humankind's perceived separation from nature was prevalent in western societies and was even evident in early scientific research. Ecological studies from the 1950s viewed industrial systems such as cities and factories as distinct from the biosphere and outside the scope of their research; instead focusing exclusively on the effects of pollutants on natural environments (Erkman, 1997). This so-called "end-of-pipe" perspective was rather limiting as it excluded the processes that had led to the creation and emission of the environmental pollutants that were being studied. It also ignored the fundamental fact that human systems and biological systems are intimately connected due to their extensive interactions with one another. The magnitude of change required to improve the sustainability of industrial systems, such as the automotive industry, would not be possible using such a limiting perspective. An alternative approach was therefore necessary to analyze sustainable transitions in industrial systems.

3.2 Industrial Ecology: A New Interpretation of what is Natural

What is required is an alternative belief system that explicitly acknowledges the interconnectedness and fundamental linkages between the environment and human/industrial systems. Field and Conn (2007) asserted that if human systems (e.g., social, political, and financial systems) were viewed analogously to living ecosystems, much insight could be gained in terms of how such systems are designed and managed. Simply acknowledging the mere fact that humans—as well as their creations—are an integral part of nature would likely yield a number of positive implications and outcomes. Nieuwenhuis (2014) argued that dissolving the separation between what is deemed a human creation and what is deemed as natural could be the solution to resolving the many problems associated with automobility, including the use and production of automobiles. Applying a biological metaphor to the car and the automotive industry as a whole could provide insights into how sustainability is achieved and what changes are necessary to improve the environmental and economic sustainability of the car industry.

This section will examine the argument that a more useful and encompassing approach to inform the re-structuring of the automotive industry—to a more sustainable alternative—is the relatively young field of Industrial Ecology (IE). Erkman (1997) acknowledged the initial, apparent oxymoron that exists within the term "industrial ecology" given entrenched schools of thought, which suggest that human systems are not a part of nature. In a sense, the aim of IE is to dispel the belief that industry and nature are inherently contradictory. Industrial ecology suggests not only that industrial systems are fundamentally intertwined with natural ecosystems, but that they are themselves part of the biosphere (Graedel, 1996; Clift & Druckman, 2016; Isenmann, 2003). Industrial systems cannot be dissociated from their surroundings given that they often depend on various finite natural resources and ecosystem services (Erkman, 1997). Current automotive production for instance, relies on the availability of steel, which requires the extraction of iron ore from the earth.

The analogy between biological ecosystems and industrial economies that is generally agreed to have precipitated the evolution of IE to its present state stems from the 1989 seminal paper in the *Scientific American* "Strategies for Manufacturing" by Robert A. Frosch and Nicholas E. Gallopoulos, both of whom worked as researchers for the GM at the time of publication. Frosch and Gallopoulos (1989/1995) acknowledged that:

> ...the traditional model of industrial activity—in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of—should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimized, waste generation is minimized, and the effluents of one process...serve as the raw material for another process. (p. 144)

This initial description of the "industrial ecosystem" suggested that the linear flows of materials, energy, and information that define human systems and economies could become more sustainable if they were treated in a manner analogous to the circular flows of materials and energy in natural ecosystems. This concept forms the basis of the ecosystem metaphor that underpins the field of IE. Both biological and industrial systems can be defined in terms of complex flows of materials, energy, and information (Erkman, 1997, Isenmann, 2003).

Since then, an entire field of research—including the *Journal* of *Industrial Ecology*—has emerged around the concept of the industrial ecosystem. The International Society for Industrial Ecology adopted a slightly broadened definition of IE, first coined by White (1994), that expended upon the initial ideas of Frosch and Gallopoulos (1989/1995) by integrating them into the wider socio-economic context as well as incorporating the principles behind an earlier linguistic variation of IE and more analytically driven concept known as the “industrial metabolism” (IM). White (1994) wrote:

> Industrial ecology is the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use and transformation of resources. (p. *v*)

This definition emphasized the “systems view” necessary in IE’s approach. The term IM, coined by Ayres (1989) refers to the complex interactions involved with the flow of materials, water, and energy both within and between industrial and ecological systems, including natural biochemical cycles that usually operate at much greater scales, as well as the transformation of these materials into products, by-products, and effluents (Erkman, 1997; de Hond, 2000). Understanding these interactions is important as natural systems are often polluted as a result of the unceremonious reintegration of industrial materials, wastes, and by-products (Clift and Druckman, 2003). Analytical approaches such as material flow analysis, based on mass-balance principles, are used to study these interactions and are vital to IE’s toolset and its underlying vision (Erkman, 1997).

Industrial ecology takes the IM framework a step further by using scientific knowledge of ecosystem structure and function to modify industrial systems, essentially mimicking nature’s solutions to make industrial systems more sustainable (Boons & Baas, 1997; Erkman, 1997; den Hond, 2000). Also included in the scope of IE is the long-term evolutionary trajectories of key technologies that may improve the viability and sustainability of core industrial systems to encouraging sustainable development (Erkman, 1997). In a sense, this paper aims to portray two primary technologies and their evolutionary trajectory as potential solutions for the future of automotive manufacturing and as tailwinds for an alternative automotive ecosystem based on the principles of IE. By acknowledging the inextricable connection shared between industrial and ecological systems, it seems only logical to increase their compatibility with one another by making industrial systems behave more like “industrial ecosystems” (Clift and Druckman, 2016). Applying this ecological metaphor first requires a thorough understanding of the current state and function of a particular industrial system, including how the system is regulated, and what interactions it has with the biosphere (Erkman, 1997). This primary step was achieved in the previous chapter of this thesis, which considered the environmental impacts of automobility and the effects that regulation has had on the automotive industry.

3.2.1 Sustainability through Imitation

A strong thread within IE’s biological analogy is the concept of biomimicry, which involves understanding the formation, structure, or function of biological substances, mechanisms, and processes to inspire innovation in the development and design of sustainable products, technologies, and processes (Kabiraj, 2015; Lurie-Luke, 2014; Nguyen, 2006). Mimicking nature is thought to be a useful strategy for solving complex social and technological challenges. The rationale behind biomimicry and IE is essentially the same and is based on the simple observation that present-day ecosystems have evolved through mechanisms of adaptation and natural selection, throughout the earth’s 3.8 billion year history to become highly efficient (Nguyen, 2006; Nielsen, 2007). Pressing societal challenges, relating to the production and disposal of waste, and to resource efficiency and management could likely be resolved by observing solutions within ecosystems that have been naturally selected over time (Nguyen, 2006).

Janine Benyus first coined the term in her 1998 book *Biomimicry: Innovation Inspired by Nature* and acknowledged: “nature knows what works, what is appropriate, and what lasts here on Earth” (Nguyen, 2006, p. 1). Benyus described three different ways in which nature can be used to develop sustainable solutions to societal problems: (1) using nature as a model, (2) using nature as a measure, and (3) using nature as a mentor. A solar cell inspired by the photosynthetic properties of leaves in an example of using nature as a model or blueprint for the design and/or development of innovative products and processes. Solutions in nature have evolved over the course of 3.8 billion years, making it the ideal measure or standard to compare and judge innovations on their correctness or compatibility with nature (Nguyen, 2006). Lastly, nature can be used as a mentor, to gain knowledge rather than being viewed simply as a sack of resources (Nguyen, 2006). Valuable knowledge and understanding regarding the sustainability of industrial ecosystems can be gained by observing patterns and processes in nature as suggested by biomimicry and IE, more generally (Nielsen, 2007).

It should be mentioned that the scope of IE has since expanded to include thinking and practices with no real natural equivalent (Nieuwenhuis, 2014). Biomimicry is then a practical example of applying IE principles to the development and design of sustainable products. It should be recognized that biomimicry and to an extent IE, represents an ideal that may never be fully achieved in practice (Nieuwenhuis, 2014). The utility of IE according to Frosh and Gallopoulos—the founding fathers of modern IE—arises when both manufactures and consumers successfully alter their behaviour by developing new habits that more closely approach those observed in natural systems while sustaining the current standard of living within a society (Nieuwenhuis, 2014).

3.2.2 Previous Applications of Industrial Ecology

Industrial ecology emerged out of the realization that the simplified end-of-pipe approach to pollution reduction was insufficient (Erkman, 1997). Several analytical tools have emerged within IE, many of which continue to be developed and refined such as in the case of material flow analysis and life cycle assessment (Well & Orsato, 2005). A key strength of the IE perspective is its ability to study an entire system rather than just a single component at the level of an individual product, value chain, or factory. In practice however, this is not always the case. Industrial ecology is often used to achieve incremental improvements in sustainability, including waste minimization and pollution reduction, by applying strategies such as material substitution, emission reduction, life cycle analysis, total quality management, and design for the environment among other remedial actions (Wells & Orsato, 2005; Erkman, 1997). These strategies lend themselves to identifying and improving particular environmental “hot spots” rather than a truly holistic approach (Wells & Orsato, 2005).

Despite being a positive , approaches such as cleaner production (CP) and pollution prevention have been criticized for adopting an end-of-pipe philosophy by focusing exclusively on the prevention and reduction of waste rather than adopting the systems view that lies at the heart of IE (Erkman, 1997). One of the goals of IE is to replace once-through, linear material flows that contribute to society's “throw away” mentality with closed-loop cycles. As such, IE could theoretically embrace a solution whereby the production of a particular waste product is ramped up, in the absence of a feasible CP strategy, if it could be re-manufactured into a viable and marketable by-product (Erkman, 1997). However, in order for such a solution to be conceived, CP strategies and pollution prevention methods must be integrated into a system-wide perspective. The true essence and value of IE lies in its ability to provide “a systemic, comprehensive, [and] integrated view of all the components of the industrial economy and their relation with the biosphere” (Erkman, 1997 p.1).

Critiques of certain initiatives under the umbrella of IE have increased the appeal of strategies promising more than just incremental improvements (Wells & Orsato, 2005). One alternative is the concept of eco-efficiency, a management philosophy for sustainable business and production that looks to increased resource utilization—doing less with more—primarily through innovation and technological advancements (Wells & Orsato, 2005). In practice, an increase in eco-efficiency represents an increase in some measure of economic value added over some measure of environmental impact or a reduction in the total level of environmental impact (Ehrenfeld, 2005). This ratio can be used to measure and compare the impacts of alternative products and processes or potential government polices (Ehrenfeld, 2005). The difficulty in this approach lies with quantifying the level of economic value added and even more challenging the level of, and what constitutes an "environmental impact" (Ehrenfeld, 2005).

Accompanying eco-efficiency in the literature is the "factor *X* debate", which quantifies the level of dematerialization required to offset economic and population growth given the Earth's anticipated carrying capacity; the value of *X* ranges between four and 50 (Reijnders, 1998; Ehrenfeld, 2005). To achieve such quantum leaps in resource efficiency, the factor *X* debate emphasizes the importance of technology and technological innovation in "improving the environmental performance, and lowering the material intensity of economies" (Reijnders, 1998, p.14). The value of *X* generally increases over time and can be applied at varying scales to particular products or services, sectors of the economy, and the economy as a whole (Reijnders, 1999).

The premise behind the concept of "natural capitalism", a new perspective on traditional economics, is that companies can behave in a manner that is respectful of both people and the environment while also providing economic competitive advantage (Lovins & Lovins, 2001). The four principles of natural capitalism are: (1) major increases in eco-efficiency; (2) circular, closed-loop production; (3) service based business models that reward both resource productivity and circularity; and lastly (4) reinvestment into natural capital (Lovins & Lovins, 2001). A fundamental problem with an approach to sustainability based on eco-efficiency improvements is the effect of rebound. An example of the rebound effect in the automotive context is the offsetting of fuel efficiency improvements in new vehicles by an overall increase in the total number of vehicles miles travelled each year**.**

A recent concept that effectively incorporates IE's system-wide view is the "circular economy", an economic model pioneered by the Ellen MacArthur Foundation (2015) that ultimately seeks to decouple global economic development from finite resource consumption. Rather than relying on large quantities of cheap, easily accessible materials and energy for economic development, a circular economy could generate growth and create jobs while reducing the environmental impacts of material use, including GHG emissions, by maximizing the utility and value of products, components and materials in the economy at all times (Ellen MacArthur Foundation, 2015). In this way, a circular economy is restorative and regenerative by design and favours sustainable economic development by limiting the use of finite resource, material and energy, which are often associated with environmental degradation and climate change. The proposed alternative economic model presented below embodies the circular economy concept by reducing material and energy flows throughout every facet of the automotive industry and all life cycle phases of the automobile.

Graedel & Lifset (2016) provided a comprehensive account of IE tools developed by industry between 1990 and 2000. The majority of these tools emerged out of corporate initiatives aimed at enhancing a company's competitive advantage through the simplification of product assembly and disassembly, and aimed at reducing fixed costs through resource reuse, recovery, and recycling, among others (Graedel & Lifset, 2016). Unlike most scientific disciplines, IE is firmly rooted in industry and governmental policy. Although seldom altruistic, the ideas that underpinned these often uncoordinated and ad hoc initiatives eventually developed into an academic specialty. Given the focus of this thesis, it is an interesting coincidence that one of the most instrumental corporate initiatives during IE's seminal period was pursued by Swedish car company Volvo. Alongside Swedish academic and government organizations, Volvo was one of the first companies to develop a life cycle impact assessment for use in product development and planning (Graedel & Lifset, 2016). The various tools that are now included under the umbrella of IE demonstrate the myriad opportunities that exist to improve sustainability, allowing development in both emerging and advanced economies to continue without compromising the environment and its natural carrying capacity in the future (Wells & Orsato, 2005). Provided its origins in industry and policy development, the principles and strategies that underpin IE should be used by industry practitioners to identify efficiencies in production, resource use, and waste disposal for the purpose of improving profitability and increasing competitive advantage

(Erkman, 1997). An economic structure that was based on the principles of IE would therefore be more intelligent and more elegant than society's current "take, make, dispose" economic model (Erkman, 1997).

3.2.3 A Manifestation of Industrial Ecology

One of the earliest quintessential examples of IE in practice manifested itself in the form of Denmark's eco-industrial park (EIP) at Kalundborg. The cooperative arrangement involved the sharing of resources such as water, energy and material by-products between closely situated firms. The industrial symbiosis that was created among these firms ensures that the large amount of industrial output that is not part of the intended artifact is maintained within the economy as opposed to being unceremoniously returned to the environment as waste (Ehrenfeld & Gertler, 1997). Eco-industrial parks promise a win-win scenario with benefits for both the environment and the economy (Ehrenfeld & Gertler, 1997; Wells & Orsato, 2005). It is interesting to note that natural food webs can be used as a biological analogy for EIPs, encouraging the use of cyclical or closed-loop—rather than linear or open—supply chains (Erkman, 1997). The premise behind "islands of sustainability" are the same as EIPs, but expanded somewhat to include regional levels of geography. The industrial cluster in the small city of Kalundborg espouses the ideas contained in Frosch and Gallopoulos' seminal paper despite having begun its development in the 1960s. Kalundborg became such a pivotal example of sustainable industrial development because of its "extensive network of cooperating industrial operations" and "interconnected resource sharing" that many people mistakenly assume that term Industrial Symbiosis defines all of IE (Chertow & Park, 2016, p. 89). Industrial symbiosis remains today an important subfield of IE rooted in both theory and practice.

3.3 Criticisms of Industrial Ecology

Some academics have offered up criticisms of IE and have suggested possible improvements to its application. Nielsen (2007) considered whether modern ecosystem theory could be used to advance current practices of IE. The author argued that CP and IE should forgo their reliance on metaphors and integrate more concrete ecological analogies (based on recently discovered ecosystem properties) to improve their practical efficiency and functionality. Similarly, Wells and Orsato (2005) stated that "IE has been highly selective in its treatment of the science of ecology and its use of metaphor and analogy" (p. 16) suggesting that there is indeed room for improvement in the application of IE. An examination of the differences between ecological and social/industrial systems along ten target features (including, among others, component complexity, evolutionary mechanisms, feedbacks and controls, and diversity) considered relevant and potentially beneficial to CP and IE revealed a significant opportunity to embrace modern ecosystem principles (Nielsen, 2007). Nielsen (2007) proposed "an eco-mimetic development of society" (p. 1650) in which the sustainability performance of industrial systems is increased to lessen its adverse effects on the environment while simultaneously promoting economic growth and development using state-of-the-art ecosystem theory.

Isenmann (2003) insisted upon there being greater transparency with regards to "industrial ecology's 'hidden philosophy' of nature" (p. 144) and its use of ecological metaphors and biological analogies, which he suggested are often over-emphasized or inadequate as a result of a rather one sided and romanticized view of nature in general. To clarify IE's interpretation of nature as a model, Isenmann (2003) proposed a set of philosophical arguments to ensure the proper epistemological application of metaphor and analogy within scientific research. When used as a model within IE, nature is used to gain both theoretical and practical insights on the *ideal* use of natural resources and ecosystem services. Isenmann (2003) criticized the idea that nature can be imitated, as is suggested by the concept of biomimicry. He considered the insinuation that nature offers itself as a blueprint or template ready to be copied to be not only unproductive, but impossible to do without simplification. Nature must first be interpreted by human language before it is translated into human language, distorting the human elucidation of natural processes and phenomena. Isenmann (2003) did not denounce the use of metaphor and analogy in scientific research, suggesting its use can be legitimate and even helpful if used to clarify new insights in the context of discovery and further their communication within the context of application but warned that grave errors potentially await researchers if used for the purpose of "proving a proposition or even to establish a presumption in its favour" (p. 151).

Boons and Baas (1997) pointed to a fundamental difference between biological and industrial systems. Biological systems will often achieve a local equilibrium state because of evolutionary mechanisms at the level of organism (i.e., variation, selection and reproduction). A local equilibrium is achieved when ecosystem function reaches a highly—though not necessarily optimally—efficient state (Boons & Baas, 1997). Equilibrium states occur because the rate of evolutionary adaptation is often faster than the rate of environmental change or the frequency of environmental disturbances that disrupt ecosystem function. The fact that ecological systems evolve to reach such highly efficient combinations of organisms provides the fundamental justification for IE's ecological metaphor: using nature as a model for the efficient use of materials, water, energy, and by-products. A potential simplification of this metaphor, as noted by noted by Boons and Baas (1997), is the inherent ability of ecological systems to approach optimum efficiency independently through a sort of algorithmic process. Industrial systems on the other hand, are often governed by competition, which does not necessarily ensure a continuous progression toward greater efficiency. In the absence of altruistic corporate objectives, industrial systems require the conscious participation of external actors to achieve increased efficiency in resource use.

Along a somewhat similar theme, Peterson (2000) noted that unlike natural systems, which rely solely on past events and circumstances for adaptation, industrial systems have the advantage of human insight and, therefore, the benefit of informed decision-making based on this foresight to enhance the efficiency of industrial systems. Industrial ecology requires the integration of entire—or at least partial—product chains within a given region to reduce the environmental impacts of economic activities. Companies must therefore reduce their desire for corporate autonomy and embrace cooperation with other—possibly competing—firms (Boons & Baas, 1997). Firms clustered within a particular geographic region are not necessarily going to be dependent upon one another or be able to form an industrial symbiosis automatically. Because of this, Boons and Baas (1997) emphasize the importance of coordination, with respect to industrial activities, economic actors, and governmental agencies, in achieving the goals of IE. Coordination does not itself guarantee inter-firm cooperation, which requires a delicate mix of both cooperation and competition (Boons & Baas, 1997).

Determining this mix requires the intentional actions of an initiating organization (with an ability to lead stakeholders), government agencies, or business/industry association to ensure the cooperation necessary in achieving an industrial ecosystem and to catalyze development and innovation within product and material life cycles (Boons & Baas, 1997). Despite these dissimilarities, IE's ecological metaphor underlines the importance of recognizing and understanding the interrelatedness of industrial processes in order to reduce adverse environmental impacts (Boons and Baas, 1997).

Industrial ecology will form the basis of the theoretical perspective used in the following chapter to identify an alternative business model and paradigm shift for the automotive industry given the identification and analysis of current economic and environmental trends in the global automotive industry that have been argued to no longer be sustainable moving forward.

Chapter 4 Applying Industrial Ecology to the Automotive Industry

The convergence of regulatory and market pressures in the automotive industry has raised doubts about the continued viability of the industry's prevailing paradigm which has remained relatively unchanged since its inception nearly a century ago. As outlined in Chapter One, incumbent VMs have attempted to mitigate the negative impacts of changing circumstances within the industry by adapting their business with a variety of strategies to increase economic efficiency. The majority of these strategies, however, are aimed at reducing costs by increasing complementarities and economies of scale. Dramatic leaps in sustainability are unlikely to occur provided the confines of standard practice and conventional logic in the automotive industry. As scrutiny over the industry's poor sustainability performance rises and contexts shift, the inevitability of a radical or unprecedented transformation in the automotive industry will continue to increase. This chapter will introduce a potential alternative model, theorized by Dr. Peter Wells and Dr. Paul Nieuwenhuis—both of whom have vast knowledge of and experience studying the automotive industry, which is argued to be more sustainable both economically and environmentally than the dominant production and consumption paradigm.

The theoretical concept, known as Micro-Factory Retailing (MFR), was developed using insights from the burgeoning field of IE and is rooted in the economic theories of distribution and decentralization. The last chapter provided a literature review of IE that outlined its early development; its core concepts and principles; some of its earliest practical applications; as well as some ideological critiques. The forthcoming sections of this chapter will outline emerging approaches to sustainability in the business literature, how IE can be used to improve the sustainability of the automotive industry, and possible conclusions that can be drawn from applying an ecological approach to this particular industrial sector. Specific details about the proposed alternative will also be described to distinguish it from the status quo.

4.1 Limits to Industry's Current Approach to Sustainability

Sustainability has increasingly become a prominent theme in facets of the business literature concerned with supply chains and networks. Burgess, Hwarng, and De Mattos (2002) conveyed the importance of efficient inter-organizational relationships (a concept in IE) by suggesting that "the competitiveness of a company at the head of a supply chain (i.e., facing the consumer…) depends upon [its] ability to manage the rest of the supply chain to maximum effect" (as cited in Wells & Orsato, 2005, p. 18). Enterprises are thought to gain a competitive advantage by improving their extended supply chain through techniques such as "value stream mapping" and "supply chain agility." Similar concepts therefore emerged in the automotive industry. One of the pillars of lean production, when it arrived in North American in the 1990s, was the elimination of waste in the form of large component and part inventories, in favour of JIT delivery.

Green supply chains, reverse logistics, and remanufacturing all emerged out of a similar effort by supply chain managers to reduce waste and cost by increasing efficiencies throughout their logistics network (Wells & Orsato, 2005). Aside from regulatory compliance, VMs also began adopting cleaner manufacturing techniques to increase their resource productivity—via energy and material conservation—for pecuniary reasons (Wells & Orsato, 2005). Along with increased investments in environmentally related research and self-imposed voluntary environmental targets, many global OEMs began releasing yearly environmental reports in the latter half of the 1990s addressing such topics as vehicle emissions reductions, alternative drive and fuel systems, and end-of-life vehicle (ELV) recycling strategies (Wells and Orsato, 2005).

These attempts, although valuable, were not sufficient on their own to bring about the quantum leap in eco-efficiency required in the automobile industry, as suggested by the aforementioned factor *X* debate. They also fail to take advantage of IE's strength as a holistic approach that can encompass entire economic sectors or industries in its scope of analysis. Wells and Orsato (2005) have pointed out that the basis of analysis of many IE studies has remained at the material or process level—favouring incremental environmentalism over radical disruptions to increase sustainability. To successfully redesign the IE of the auto industry, Wells and Orsato (2005) have insisted that the scope of analysis must expand beyond that of extended supply chains to include the *organizational field*, a concept developed by Dimaggio & Powell (1983). The IE of the automotive industry must address environmental impacts associated with all phases of a vehicle's life cycle, from the extraction of raw materials to the disposal of ELVs, and include all stakeholders involved throughout the value chain (Wells & Orsato, 2005).

The industrial ecosystem of the automobile is comprised of a series of actors and stakeholders including VMs; parts and component suppliers; car dealers/distributors; accident repair and maintenance facilities; fuel suppliers; suppliers of car related materials such as engine oils and windshield washer fluid; government funded roads and related infrastructure such as bridges; and facilities tasked with recycling and disposing of ELVs (Nieuwenhuis, 2014). In order for this industrial ecosystem to become more sustainable, it must reconcile the competing—and sometimes contradictory—needs of the environment, society, and the economy, a task Wells and Orsato (2005) argued cannot be adequately achieved given the current state of IE.

Measurable improvements have indeed been made in the automotive industry—particularly concerning the reduction of toxic emissions—over the last quarter of the twentieth century. However, despite efficiency improvements from new engine technologies, reductions in CO_2 emissions have mostly been offset by rebound effects related to average increases in vehicle weight, acceleration, and top speed (Wells & Orsato, 2005). In the same way that the industry has been unable to reduce net CO_2 emissions from personal transport, measures taken by automakers to improve their environmental performance, although not insignificant, have brought to light fundamental limits in the contemporary logic that preclude them from making dramatic sustainability improvements (Wells and Orsato, 2005).

Ford's River Rouge assembly plant in Dearborn, MI is a good example of these imposed limits. The assembly facility underwent significant renovations to display the company's improved environmental performance and state-of-the-art manufacturing efficiency. The River Rouge plant was outfitted with a host of environmentally friendly innovations such as a green roof, reduced storm-water runoff, and a phyto-remediation project to address soil contamination at the site (Tukker & Cohen, 2004). Although advantageous, the overall strategy underpinning the facility's improvements fell short of a true systems approach and the essence of IE. The green facility was used to assemble the company's best-selling F-150 pick-up truck. By failing to take a holistic approach, Ford ignored the life cycle impacts of the products it manufactures and a significant source of GHG emissions (Tukker & Cohen, 2004).

This example supports the general presumption that the level of eco-efficiency improvements conceivable within the contemporary logic of the automotive industry are bound by fundamental limits set by its entrenched production process and product technology, which set the parameters for the industry's dominant business model. These constrains significantly reduces the number of alternative solutions available to VMs. The dominance of the all-steel car body and the ICE in the auto industry have co-determined the prevailing vehicle design and manufacturing process that define the contemporary automotive industry and together have favoured incremental rather than radical efficiency and sustainability improvements (Wells & Orsato, 2005). The existing paradigm has, to an extent, forced VMs to pursue strategies that uphold the dominant technological regime by increasing economies of scale to reduce costs.

According to Wells and Orsato (2005) the "primacy of least cost manufacturing economies of scale" (p. 18), which they contend is a major determinant of the automotive industry's scale, capital structure, and dominate business model, is a key limit of the existing paradigm. Similarly, Wells & Nieuwenhuis (2004) insist that sustainability cannot be achieved in the automotive industry unless issues of scale and capital structure are addressed. The researchers argue that it is structurally impossible for OEMs—given the status quo—to fully achieve the laudable goals of the corporate sustainability programs that are often put forth to promote their commitment to sustainability.

The corporate scale, capital structure, and business model employed by most global VMs is intimately related to the product design and manufacturing process they employ, which result in the contemporary patterns of consumption and production defining the automotive industry (Wells & Orsato, 2005). These patterns requires significant plant-level economies of scale in manufacturing to lower per-unit costs and ensure high enough sales to justify the large capital costs of the specialty equipment and automated tooling involved in manufacturing all-steel car bodies and ICEs. It is estimated that economies of scale in the automotive industry can be as high as 5 million units per annum for R&D, two million units per annum for pressed steel panels, one million units per annum for engine castings, and 250 thousand units per annum for final assembly (Wells & Orsato, 2005). These figures essentially determine the minimum allowable production scales to remain economically viable.

The standard capital structure of the automotive industry may have been economically efficient for vehicle manufacturers when consumer demand could justify production above high break even points (i.e., assembly plants must often operate above 85% capacity to be profitable) but also supports a dominant product design and manufacturing process that is quite inefficient from an environmental standpoint (Wells & Orsato, 2005). These factors have all contributed to a business model that not only encourages—but also relies upon—perpetual mass consumption of new products to generate profits. Vehicle manufacturers do not traditionally benefit from any of the downstream value generated by the in-use-phase of the vehicles they produce (Wells &Orsato, 2005). Mass consumption is not possible without mass production, suggesting a more sustainable economic model must address both of these systems. The mass production system in the automotive industry helps drive mass consumption and should, thus, be addressed first when envisioning a more sustainable automotive paradigm (Nieuwenhuis, 2008).

4.2 Improving Industrial Ecology's Theoretical Framework

Wells and Orsato (2005) contended that if IE is to effectively inform the redesign of the automotive industry, it must also broaden its ecological analysis to include a wider range of topics such as diversity, resilience, and scale. They argued that the state of IE was, at the time, theoretically limiting and limited due to the selective nature of its ecosystem metaphor and biological analogies. Traditionally, IE has been useful as an analytical tool for identifying and describing *what is* (i.e., contextualizing current challenges) rather than being the prescriptive tool Wells and Orsato (2005) envisioned for it, suggesting instead, *what could be* (e.g., guiding the implementation of and the decision making process around innovative strategies and solutions for a more sustainable future). To date, IE has not been widely applied in this manner. By considering economic scale and organization—within and between firms—as part of the analysis, Wells and Orsato (2007) hoped to demonstrate "the real power of industrial ecology as an organizing theoretical framework for the redesign of an entire sector of economic life" (p. 17), in this case the contemporary automotive industry.

A key consideration that emerged out of the EIP concept—one of the clearest manifestations of IE in practice—is the significance of transportation. Whether it is the transportation of raw materials or components for the production of goods or the transportation of assembled products, there is an environmental cost and risk associated with it. These impacts must be considered when proposing a model for the redesign of an industry producing a product as complex as the automobile, with thousands of individual components having sometimes distant supply chains. This consideration led Wells and Orsato (2005) to expand the scope of IE to include aspects of economic scale and industrial organization. It is unlikely that a future automotive ecosystem could support local supply lines into geographically dispersed factories, making spatial form a vital consideration for any proposed alternative. Nieuwenhuis (2008) explores the notion of diversity, scale, and resilience and suggests that a more sustainable alternative model for the automotive industry might already exist within the contemporary automotive industry and exemplify some aspects of the proposed MFR model.

4.3 An Ecological Approach to Transforming the Automotive Industry

Nieuwenhuis (2008) draws on the notion of diversity, which refers to the level of variety and variability within a system, to improve the sustainability of the automotive industry. Diversity affects both the productivity and stability of ecosystems as it can provide a mitigating effect or buffer against environmental change (Tilman, 2000). Ecosystems that are more diverse can spread environmental variability across a greater number of species, which tend to respond to change independently, in the same way that a more diversified investment portfolio is less volatile and carries less risk given unexpected market shifts (Tilman, 2000). The significance of diversity is most apparent during periods of change as it often determines a system’s ability to respond and adapt to environmental change, since natural selection has fewer adaptive pathways or “building blocks” upon which to draw (Folke, 2006).

A related concept is that of ecosystem resilience. Perrings (1998) recognized two different, but related definitions for ecosystem resilience:

1) The time required for a disturbed system to return to its initial or undisturbed equilibrium state (i.e., the speed with which a systems returns to equilibrium), and

2) The magnitude of disturbance a system can withstand before it is forced into a new stability domain or local equilibrium state.

The link between ecosystem resilience and diversity remains inconclusive, though one perspective suggests that system resilience is dependent on the range of species available to maintain and support the critical system functions and processes under a variety of environmental conditions (Perrings, 1998). This eludes to the presence of redundancy: species with no apparent value within the current structure or function of the system. Perrings (1998) argues, however, that redundancy does not necessarily equate to an absence of ecological value.

For instance, a previously unproductive species may, under a new set of environmental conditions, become highly valuable given a new equilibrium state (Perrings, 1998). Likewise, dominant species could be made redundant given a change of state. The degree to which the loss of a species will influence a system depends upon the number of alternative species capable of fulfilling its role or function, suggesting a diverse mix of species is an important factor in determining the resilience, and therefore the stability of an ecosystem (Perrings, 1998). Could it be true that variability in the automotive industry offers a similar benefit it terms of system resilience and stability?

Diversity arises naturally as a result of spontaneous genetic mutations but also because of competition between species. In the automotive industry, competition prevents any one automaker from achieving a monopoly and restricts each automaker’s total market share. Consider for a moment a forested ecosystem where tree species with the largest canopy benefit most from the incoming solar radiation gradually reducing the amount of available sunlight that is able to penetrate through the canopy as it moves closer to the forest floor, where there may only be a fraction of radiation available if any at all. A similar structure or gradient could be said to have developed within the contemporary automotive industry where higher volume brands like VW, Toyota, GM, Ford, etc. compete directly with one another for the mass market consumers (the largest share), while premium brands like BMW, Mercedes-Benz, and Audi compete with one another for a share of the luxury performance vehicle market which represents a subset of total vehicle market share and involves less price sensitivity than mass market consumers. The higher profit margins on premium vehicles motivated some mass-market producers to enter into the segment to expand their market share and improve their profitability performance by establishing their own premium brand or by acquiring an existing brand (i.e., Honda/Acura, Toyota/Lexus). The gradient between consumer segments is what allows automakers to expand their reach upmarket without cannibalizing on their existing market share. Although cross shopping can occur, Toyota’s core target market for instance is different from that of Lexus. Further down the gradient, specialized producers like Ferrari and Porsche operate within small niches and even finer still, manufacturers of exotic sports cars and supercars such as Spyker, Pagani, Lotus, Bugatti, etc. compete with one another in much smaller volumes for a very specific share of the consumer market (Nieuwenhuis, 2014). This pattern of competition in the automotive industry and the resulting structure alludes to two important consideration: the role of redundancy and scale.

4.3.1 Resiliency and the Effects of Scale

Resilient ecosystems tend to have apparent redundancies in species composition and sub-systems that allow them to persist—albeit in an altered form—after experiencing a disturbance (Nieuwenhuis, 2014). However, species can be divided into functional groups, based on their ecological role, as well as by the specific scale in which they operate and function (Peterson et al., 1998). Ecological resilience is derived from: (a) overlapping functions within specific scales among species of different functional groups; and (b) functional reinforcement among species at different scales sharing a common function (Peterson et al., 1998). Cross-scale resilience minimizes competition, which suggests that scale is one of the determinants of inter-firm competition. Species or firms that may appear redundant due to overlapping functions may not compete with one another—despite sharing select resources—because they exist and operate at different scales (Nieuwenhuis, 2014). Despite sharing a common function or purpose, by exploiting different scales, firms may experience the same environment quite differently, and be affected by and respond to market changes differently as they often do not affect an entire system uniformly.

Firms operating at various scales are equally important. The apparent hierarchy created by scale differences are not representative of their relative value within a system, whose function is dependent on the multitude of complex interactions among all its parts (Nieuwenhuis, 2014). In the context of industrial symbiosis, this so-called "scale effect" suggests that the relationship between firms operating at different scales should be mutually beneficial, perhaps through resource sharing or the re-use of industrial by-products, while simultaneously minimizing competition between them (Nieuwenhuis, 2014). However, because of the interconnectedness that exists between the various scales, the loss of species at any particular scale can make the system more vulnerable and less stable. The supply of engines from Ford and BMW to Morgan, a specialty manufacturer of coach built automobiles, and the financial bailout of Chrysler and GM are good examples of the important role that firms at various scale have for the system as a whole.

The mechanisms of change for an industrial transformation may not be fully understood but previous technological transitions in the automotive industry may offer up some clues, most notably the transition from composite wood frames to all-steel car frames or bodies. It is common for elements of an alternative model to exist in some form within the dominant economic paradigm, or even, for several viable models to operate side by side within an industrial system. The latter case could be argued to exist in the automotive industry. The mass production model was not the only viable manufacturing strategy that was in existence at the time of its introduction. However, it became dominant because of the particular set of circumstances that had been created at that time. Those circumstances however have since changed; suggesting that perhaps the current production system is not optimal given the circumstances that exist today in which demand in mature markets is stagnant, resulting in perpetual issues of overproduction and overcapacity. There is significant evidence to suggest that the status quo is inefficient given the context of strengthening environmental and market pressures. It can also be argued that the industry's dominant business model—an outcome of the industry's scale and capital structure—will not be suitable in the future to adequately serve the needs of an increasingly diverse consumer base that is demanding more personalized mobility products, solutions, and services, such as electrification, shared-mobility, and ride-hailing services.

Global VMs whose core competencies are deeply entrenched in the dominant business model will intuitively downplay the significance or the inevitability of a major transition in the industry because not only do they benefit from the current structure but they have also invested a significant amount of capital into the existing production system (Wells & Orsato, 2004; Nieuwenhuis, 2008). In the absence of regulatory requirements, economic imperatives will always supersede environmental concerns. Industrialists often mistakenly view the environment as a subset of the economy, when in reality both economic and social spheres are embedded within the environment (Nieuwenhuis, 2014). Economies depend on natural resources while societies depend on people, both of which emerged out of the environment. An alternative automotive ecosystem must create viable economic opportunities without sacrificing environmental quality or human health. It must be sustainable.

4.3.2 Identifying Resiliency in the Status Quo

Among those who recognize the necessity for a transformation in the automotive industry, there is less clarity on how such a change will occur or what such a change might look like. Nieuwenhuis (2008) observed that a few specialized automotive producers who have remained economically viable over the long term—using a business model that was distinct from the one used by mass-market producers—by operating along the fringes of the current automotive paradigm. Based on this evidence, the researcher suggested that these so-called fringe business models could represent possible alternatives for the future that are much more sustainable. Nieuwenhuis (2014) later suggested that aspects of the proposed MFR model are already evident within the business models of existing small-scale producers that, in his opinion, hold the key to the impending paradigmatic shift in the automotive industry. Some of these smaller fringe automakers are housed under the corporate umbrella of mainstream brands such as FCA, which owns Alfa Romeo and previously owned Ferrari while VW's parent company oversees Porsche, Bentley, Lamborghini, and Bugatti. These smaller specialty manufacturers make the automotive ecosystem more resilient in the analogy by Nieuwenhuis (2008) since:

> Any disturbance that affects the mass producers as a result of the twin pressures of diversifying markets and the need for more sustainable economic structures may leave the small-scale specialists relatively unaffected—to an extent they are able to operate within the confines of their own sub-system. (p. 156)

The continued success of these highly specialized producers suggests the presence of alternative business models that could be used to improve the industry's economic and environmental sustainability if they could be made viable on a greater scale and at a lower cost using the proposed theoretical business case known as MFR and the innovative product and process technologies outlined in this thesis.

It could be argued that specialized producers also add diversity to the automotive industry, making it more resilient. For example, *Forbes* magazine recently reported that Volkswagen AG's high-end luxury brands Porsche and Bentley were its most profitable divisions, accounting for nearly 18% of the company's total valuation despite only representing 1.5% of its net sales volume. According to *Forbes'* estimates, the EBITDA margins for the Porsche, Bentley division is nearly 40% while adjusted margins across all the company's brands was only 14% (Trefis Team, 2014). The difficulty lies in the high price premiums demanded by these fringe producers given that they operate at much lower volumes and benefit from fewer economies of scale. Despite this challenge, Nieuwenhuis (2014) suggests that if these specialized business models were moved from the fringes to the mainstream, the industry would be more sustainable. Desirable features of these fringe business models include an emphasis on customization; a build-to-order production system, preventing capital from being locked up in unsold inventories of new vehicles that must often be discounted using sales incentives to move them off dealer lots; and the involvement of end-users in the manufacturing process to encourage an emotional connection between consumers and their vehicle to ideally reduce the rate of premature replacement and upgrading due to technological obsolescence.

However, previous attempts to make smaller niche brands more mainstream within the current system have been met with difficulty or failure. Ford was unable to find success with Jaguar-Land Rover, selling off the brands just prior to the 2008 recession, while GM was a significant factor in the demise of Swedish automotive brand Saab whose assets were dissolved in 2010 when it was bought by the small Dutch auto group Spyker, a brand that was resurrected in 2000 as a manufacturers of exclusive coach-build super sports cars (Ahlander & Bailey, 2010). These examples suggests that in order for such business models to be brought into the mainstream there must first be a fundamental shift in the dominant production technologies that are used to manufacture and assemble contemporary automobiles. Given that current specialty automakers demand a significant cost premium, it is essential that any effective alternative technology be able to produce affordable vehicles without relying on economies of scale as the primary mechanism for lowering production costs. The following chapter will attempt to outline a potential technological pathway to facilitate a transition towards MFR, a theoretical business model based on concepts from IE and from fringe automakers operating within the current automotive paradigm.

4.4 Micro-Factory Retailing: A Theoretical Model for a Sustainable Future

Micro-factory retailing is a theoretical business concept based in decentralized and distributed economics that is considered a more sustainable model, both economically and environmentally, than the automotive industry's current production and consumption paradigm (Nieuwenhuis, 2014/2008; Wells & Orsato, 2005; Orsato & Wells, 2007). This alternative model would require "a radical reshaping of the relationship between product technology, process technology, business organization, and the purchase and use of cars" (Wells and Orsato, 2004, p. 376). Essentially, the MFR model involves completely redesigning the automotive ecosystem so that it will more accurately align with recent shifts in consumer preferences and regulatory requirements—particularly in the mature markets that are symptomatic of the challenges associated with the current mass production system. Since its inception, no other business model has successfully competed against the economies of scale achieved with mass production (Wells & Orsato, 2004). The keystone of the MFR model is its rejection of least cost manufacturing economies of scale and centralized mass production facilities with an average breakeven point of 250 thousand units per annum (Wells & Orsato, 2004). Assuming a full transition to MFR, the same production capacity would be spatially dispersed across many small-scale, local or regional production facilities.

In practice, Wells & Orsato (2004) suggest that the same production capacity (i.e., 250,000 units) could be distributed among 50 different production sites situated to match concentrations in population each producing 5,000 units annually as opposed to a single, centralized assembly plant. Multiple low-volume facilities serving the markets in which they are located are inherently more flexible and adaptable. For instance, production levels would more easily be adjusted to reflect the market and demand fluctuations. Greater value creation and an emphasis on downstream activities means that these micro-factories would be less susceptible to closures during periods of slow demand. The economic viability of MFR is not solely embedded in the sale of new vehicles but equally in the value opportunities available once a vehicle has been sold. In the rare occurrence that a plant must be shuttered, the social impacts of the closure on the local community would be much less dramatic. Employment losses from traditional plant closures can easily devastate a community and make it much more difficult to redistribute those jobs among other sectors of the economy. Reduced resource utilization is also a goal of MFR by increasing the longevity of vehicle life cycles and engaging in take-back programs to ensure the proper disposal and recycling ELVs.

As its name suggests, MFR eliminates the distinction between manufacturing activities and retail sales. Under the current system, the consumer interface is managed by third party retail franchises or car dealerships who are responsible not only for the sale of new and used vehicles, but are also responsible for vehicle aftercare, maintenance, and repair. Under the current system, VMs do not participate in any downstream value capture and have very little direct contact with their consumers. In the MFR scenario, the consumer interface would be controlled by the VMs themselves at the micro-factory. The distribution of micro-factories would reflect spatial patterns in population to match demand (Wells & Orsato, 2004). The reduced spatial footprint of micro-factories would allow them to be located within—or at least much closer to—metropolitan areas, where the highest concentrations of population exist. Micro-factories could be located on existing brownfield sites in need of redevelopment as opposed to premium greenfield sites.

These factories would not only house assembly and sales activities of new vehicles, but would also expand their activities to include vehicle maintenance, service, and repair. Value could also be generated through the sale of spare parts; retrofitting and upgrading older models with new features and technologies; as wells as trade-ins and ELV recycling and disassembly. Micro-factories would engender sustainability within local communities through their production process, production technology, and through product stewardship and recycling. After-sale activities, such as maintenance and upgrading, would become increasingly important to car manufacturers that would rely less on the sale of new vehicles to generate value and more on value added activities traditionally not captured by VMs. Producers would have a stake in increasing the longevity of their products given their newfound participation in downstream value capture. Manufacturers would be inclined to foster a trusting relationship with their customers that extends beyond the initial sale of a product and continues throughout the life cycle of the vehicle. This new dynamic between producers and consumers would ideally prevent or delay premature vehicle scrappage through trade-ins, in which the old vehicle could be upgraded and/or refurbished for resale, or by offering to retrofit the vehicle with the newest features and/or technologies. Electric VM Tesla Motors is already offering this type of service, to an extent, through mobile, cloud-based software updates to enhance vehicle performance and provide additional features or upgrades to vehicle systems like semi-autonomous driving functions (i.e., Tesla's autopilot).

In terms of economic impacts, current sales channels and retail outlets would be eliminated, while automotive repair and maintenance centers would also likely experience a significant decrease. However, Wells and Orsato (2005) argue that MFR "clearly resonates with social and political objectives" (p. 23) as it will generate meaningful local employment and wealth creation through a network of small-scale manufacturing and retailing facilities. Consumers would have the opportunity to visit the factory that is building their vehicle and know that their purchase was having a direct, positive economic impact on the local or regional economy. Given the centralized nature of existing production activities in the automotive industry, it is likely that areas with a high concentration of auto sector jobs would experience a decrease in employment from plant closures. Indeed, the closure of existing mass production facilities would likely result in some negative employment outcomes for regions, like Ontario, which currently has a high proportion of auto sector jobs. It should be noted however, that the existing system was already vulnerable to plant closures, with several successive rounds of rationalization and relocation resulting in plants within the TRIAD closing while new capacity was being created in emerging economies (Wells & Nieuwenhuis, 2004). Some jurisdictions could experience a net increase in auto sector employment, as fewer cars would need to be imported from abroad. Regions without previous employment from the automotive sector would likely benefit from the construction of micro-factories based on patterns of demand and population.

The industry's existing paradigm was able to remain economically viable because of high plant level economies of scale. The MFR concept fundamentally rejects this core principle. As previously discussed, spatial structure and scale are an important consideration when attempting to reshape and redesign an entire sector of economic life. It is unlikely that local supply chains would develop around micro-factories in the same way that automotive suppliers have traditionally concentrated themselves around large automotive assembly plants, specifically to accommodate JIT delivery, whereby only the parts and components needed on the factory floor at a particular time are delivered to the production line, and leaner manufacturing. The MFR model would generate external or industry-wide economies of scale rather than at the plant level (Wells & Nieuwenhuis, 2004; Wells & Orsato, 2004). Critical suppliers would be strategically located and highly automated to generate economies of scale in the production of generic modules and powertrains that could then be distributed to networks of decentralized micro-factories so that they could maintain some of the economic benefits associated with high-volume production (Wells & Orsato, 2004). The parts and modules chosen for mass production would be carefully selected, most likely consisting of components not readily visible to the consumer to maintain product differentiation and uniqueness. One likely component that would benefit from the cost savings of mass production are batteries and powertrains for EVs.

A shift to MFR could benefit consumers in a variety of ways (Wells & Orsato, 2005). First off, consumers would benefit from a reduction in vehicle depreciation. In the current context, the adage is that vehicles lose value immediately upon leaving a dealership’s lot. Depreciation is caused by a combination of factors, including vehicle wear and tear; overproduction and subsequent discounting of new vehicles; and the frequent introduction of new or “refreshed” models (Wells & Orsato, 2005). The MFR concept could reduce the effects of the latter two factors on vehicle depreciation. Micro-factories would be well suited to use a technique already used by small-scale, prestige automakers in Europe, which offer customers the ability to tour the facility and meet the individuals who build their vehicle in order to increase consumers’ emotional attachment to their vehicle and hopefully increase the likelihood that they will want to extend its useful life cycle while also reducing instances of premature disposal or recycling (Wells & Orsato, 2005).

Consumer satisfaction might also be improved thanks to the direct participation of vehicle manufacturers at the consumer interface. Such interactions could provide manufacturers with a firsthand account of their consumers’ lifestyle, aspirations, and mobility needs as they arise and as they change over time. This information could drive consumer-focused development and designs that meet the specific needs of the local population and allow for much greater product differentiation and specialization (Wells & Orsato, 2005). The added flexibility inherent in MFR would make such customization possible through shorter lead times and late configuration, unlike the traditional model, which is crippled by long logistic chains and spatially distributed retail locations (Wells & Orsato, 2005). The ability to quickly respond to consumer orders and adjust production levels to consumer demand gives MFR a distinct advantage over the traditional model. Modular vehicle design and production would ensure that individual micro-factories could feasibly provide a range of different vehicle configurations (e.g., sedans, hatchbacks, station wagon, and crossover utility vehicles [CUVs]).

4.5 Conclusion

Micro-factory retailing represents an ideal—a possible vision for the future in which the relationships existing between product technology, process technology, business organization, and the sale and use of cars is radically reconfigured to improve economic and environmental sustainability (Wells and Orsato, 2005). The hypothetical structure put forth by MFR did not claim that that is was the only solution for achieving sustainability in the automotive industry, however, it should be considered as a potential pathway for combating the increasing environmental and economic pressures facing the automotive industry (Wells & Orsato, 2005). Small scale-production provides flexibility, allowing VMs to be better positioned to satisfy an increasingly diverse range of consumer needs and demands for which the mass production system is ill suited to provide (Nieuwenhuis, 2008). Concepts of mobility, especially in mature automotive markets, are beginning to change and will soon require new and improved business models capable of accommodating them. For instance, the focus on vehicle ownership is shifting somewhat towards more sustainable notions of mobility including mobility-as-a-service (MaaS) and car sharing schemes. Given these trends, it appears likely that OEMs will in the future be much more involved in traditional downstream activities as they reposition their business models to accommodate shifting consumer preferences.

Industrial ecology not only provides a basis for understanding the potential benefits of a model such as MFR, but could also provide a means of verifying that the impacts and outcomes of such a transition are in fact desirable and effective at improving the sustainability of the industry. All phases of the product life cycle, from the extraction of raw materials to the disposal of final use products, and everything in between must be considered when attempting to study the sustainability of an economic sector (Wells & Orsato, 2005). It is highly unlikely that a single solution will solve the sustainability problem facing the automotive industry; rather it is more likely that a multiplicity of different solutions co-existing in time and space will work together to improve the long-term sustainability of the automotive industry (Wells & Orsato, 2005). It is also likely that both established OEMs and innovative new entrants will have a role in orchestrating a transition in the industry. The tools of IE could be used to compare and contrast various models and/or alternative structures for the automotive industry as well as various combinations of different strategies. Research into the IE of the automotive industry could act as a platform to advocate for political and regulatory changes necessary to promote and hasten the development of more sustainable business models and economic structures on the supply side of the automotive industry.

Chapter 5 Driving Change with Technological Innovation

An assertion held by the researchers who developed the conceptual MFR framework was that the production technology used to manufacture Budd-style all-steel car bodies is too capital-intensive and is economically viable only at high volumes with significant economies of scale. The high volumes generated by mass production necessarily entail strong and steady demand (i.e., mass consumption) to be successful. There is mounting doubt as to whether this production and consumption paradigm can remain viable given the imperative of future, long-term sustainability and increasing regulatory agency. The MFR concept was developed as an alternative to the status quo to ensure future economic and environmental sustainability. That being said, MFR could not prevail within the Ford-Budd production paradigm given its dominant technologies and fundamental vehicle design. In an effort to demonstrate a plausible pathway towards MFR in the automotive industry, the following chapters will outline two niche technologies that could—if deployed properly—foster the necessary environment to facilitate a regime change via system innovation. The two technologies anticipated to have a significant—or possibly disruptive—influence on the automotive industry are additive manufacturing (AM) and electric mobility (EM). The following chapters will provide an overview of these technological innovations and their potential impact on the structure of the automotive industry. Following that, three innovative automotive companies—deploying one or both of these technologies—will be profiled in a case study to demonstrate their real-world plausibility and ability to facilitate a regime transition to MFR.

5.1 Understanding Additive Manufacturing

Additive manufacturing or direct digital manufacturing (DDM), colloquially referred to as three-dimensional (3D) printing, describes a group of technologies that allow objects to be created directly from digital data by sequentially joining together thin layers of material (Cotteleer, Holdowsky, & Mahto, 2013). The process of 3D printing is analogous to sending a digital text file to an ink-jet desktop printer. The difference between the two is that instead of depositing layers of ink, a 3D printer deposits thin layers of material (such as molten plastic polymers or fused metal alloy powders) one by one until the desired shape or object is fully formed (The Economist, 2011). Direct digital manufacturing is used interchangeably with AM and 3D printing but is preferred by some practitioners who feel the term more clearly distinguishes the technology given its explicit use of digital data (Crump, 2014a).

Grynol (2013) provided a historical timeline of 3D printing, which has evolved steadily over the last three decades and now includes thirteen distinct technologies in total (stereolithography being the first to became commercially viable in 1984). The various sub-technologies encompassed within AM differ in the type of manufacturing process they use (among 7 distinct types), the type of material with which they are compatible and the various advantages and disadvantages they offer. Descriptions of each of these technologies is beyond the scope of this thesis but can be explored further in the work of Cotteleer et al. (2013). A commonality among all AM technologies is the use of computer-aided design (CAD) software to create a 3D digital model of the object that will be printed. Once a CAD drawing has been finalized, it is converted into a simplified file format and sliced into smaller files—or instructions—each corresponding to one of the layers that are sequentially deposited by the 3D printing machine to create the physical replica of the digital files (Cotteleer et al., 2013). Once printed, objects often require some level of post-processing (e.g., sanding, filling, polishing, curing, or painting) depending on their material composition, design complexity, and the manufacturing process used.

Additive manufacturing is fundamentally different from traditional manufacturing methods (e.g., machining and drilling) which are subtractive in nature, meaning material is gradually removed from areas where it is not needed to create a desired shape (Cotteleer et al., 2013). Traditional methods are most often associated with mass production so that the high fixed costs of developing and installing dedicated tooling can be amortized over a greater number of units (Cotteleer et al., 2013). Additive manufacturing on the other hand, is most competitive at low-to-medium volumes, benefiting from economies of scope rather than economies of scale. Scott Crump (2014a), founder and CEO of 3D production systems manufacturer *Stratasys*, has contended that in order for AM to become what many are calling the next industrial revolution; its advantages must be appropriately and realistically positioned within the dialogue of its benefits and utility, and then implemented appropriately. Crump (2014a) further explains that AM is not necessarily "a cure-all or a magical solution to all that ills on the manufacturing floor" (p. 3), but is instead a viable alternative for manufacturers whose needs or expectations are not being adequately met with existing technologies or processes. Constraints and limitation inherent in traditional methods, such as injection molding and die-casting, may make it impractical to manufacture a product optimally or as desired due to time and cost impediments (Crump, 2014a).

Considerable benefits can be realized when AM is used to overcome problems or achieve specific goals that were previously unrealistic or unachievable given the utility of existing technologies and/or processes.

5.2 The Benefits of Additive Manufacturing: A Third Industrial Revolution?

It is important to distinguish AM as more than just a revision of existing methods for the purpose of accelerating the manufacturing process. This characterization fails to take into account the fundamental differences associated with AM and the numerous benefits it offers throughout the manufacturing process. In fact, AM represents a radical departure from traditional methods by altering many of the imperatives of manufacturing engineering and product design that governed what was possible (Crump, 2014a). Additive manufacturing is not dictated by barriers inherent to previous manufacturing technologies, allowing it to support new ways of thinking, new manufacturing processes and procedures, and modifications to workflows and supply chains across a wide range of industries from aerospace, to health care, automotive, and consumer durables (Crump, 2014b; Giffi, Gangula, & Illinda, 2014).

There are several distinct advantages available to companies that choose to explore and develop new internal capabilities effectuated by AM such as greater design complexity. It enables the creation of intricate shapes and patterns that would otherwise have not been possible (Cotteleer et al., 2013). The level of design freedom facilitated by AM is further enhanced by its relinquishment of traditional manufacturing trade-offs. No longer are increased costs or timelines imposed on the level of design sophistication for instance. With AM, complexity is essentially free, whereas with previous manufacturing methods, as the complexity of a design increased so too did the amount of time and money required for manufacturing (Crump, 2014b). Eliminating traditional, fundamental manufacturing trade-offs creates opportunities for innovation and promotes the optimization of product designs to match their performance parameters to their desired utility. Furthermore, AM reduces the rigidity of traditional product life cycles given the freedom to update a product's design as often as is necessary or desired and to more closely reflect the higher clockspeed of technological innovations. The added flexibility from not having to retool a production line means products can be updated or redesigned more frequently without the penalty of high costs and/or production delays. Companies can be more nimble and responsive to the dynamism of consumer preferences, an advantage when it comes to growing or maintaining ones market share (Crump, 2009b).

An extension of AM's added design freedom is its ability to enhance part consolidation, which allows the agglomeration of multiple, individual parts into a single, more complex component or module. This is conducive to other design principles including design for assembly (DFA), which seeks to simplify the assembly process, reducing time and costs by optimizing a product's design. Material waste can be reduced using DFA by limiting the number of possible mistakes or defects that can occur during the assembly process, resulting in unnecessary scrappage (Crump, 2014b). Design for assembly can also advantage supply chain management, production scheduling, and inventory control, yielding reductions in time, cost requirements, and increased quality control. Furthermore, greater control over these facets of production can be exerted by reducing the size of production runs with on-demand manufacturing, a notable advantage of AM. Manufacturing schedules can be calibrated to fluctuations in sales forecasts and inventory levels to maximize production efficiency without increasing per unit costs (Crump, 2014b).

The ability to manufacture end-use products on-demand, directly from digital data, significantly reduces time-to-market by eliminating costly production delays for new or updated products that require line retooling. Lead times for new products were conventionally measured in spans of days, weeks, or months rather than the minutes and hours that are made possible with AM (Crump, 2014b). Eliminating, or significantly reducing, the need for advanced tooling and die casts dramatically reduces the capital expenditure required to begin manufacturing. This creates an opportunity for entrepreneurial companies and start-ups looking to enter into the market, by reducing barriers to entry and mitigating the high level of risk typically involved with manufacturing (Crump, 2014a). This could facilitate greater competition between incumbent firms, which are often heavily invested in the status quo, and innovative start-ups that tend to be more nimble and flexible with fewer vested interests in the status quo.

A by-product of reducing barriers to entry is freed-up cash that can be re-allocated to other areas within an organization, including R&D for growth promotion and innovation, product development and diversification, and expansion in previously unattainable markets due to insufficient demand with respect to mass production (Crump, 2014b). Additive manufacturing is more than just an incremental improvement to replace existing technologies. It has the unique ability to encourage and facilitate radical new business models, and work flows that would have previously been unrealistic or cost prohibitive. For AM to be truly revolutionary, it must be embraced throughout companies' organizational structures and be used to promote innovation.

5.2.1 Opportunities and Current Applications

Before describing potential future opportunities for AM in the auto industry, it should be noted that VMs as well as automotive part and component suppliers have already incorporated, to an extent, AM in their production process. It is currently used to enhance existing operations, by reducing capital costs and time-to-market. Additive manufacturing is used as a decision support tool during the design phase, a quality assurance tool during the preproduction phase, and is used to build customized manufacturing tooling (Giffi et al., 2014). Rapid prototyping is likely the most common applications of AM in the industry at this time. Companies can quickly and cost effectively test several physical examples of a product's design and conduct quality trials as well as fit and finish tests before investing in the necessary tooling used in final production.

A 2013 press release celebrating the Ford Motor Company's 500,000th 3D printed auto part—a prototype engine cover for the redesigned Mustang—revealed the extent to which the company has benefited from rapid 3D prototyping of potential parts. Not only did Ford experience significant time and cost savings as a result, its part quality also improved. Engineers had the necessary time and freedom to optimize part and component designs given their ability to test multiple iterations using 3D printing, resulting in months of development time and millions of dollars being saved compared to traditional methods. Ford emphasized these benefits by comparing the time and cost requirement of prototyping an intake manifold—the most complex engine component to manufacture—using both methods. The process traditionally took nearly four months to complete a single prototype and cost $500,000. Using AM, multiple iterations of the part were prototyped in as little as four days at a cost of $3,000 (Ford, 2013). Other component types prototyped using AM are cylinder heads and air vents. Ford (2013) revealed in the press release that it intended to explore AM strategies that had yet to appear in the auto industry including application of mixed material 3D printing, continuous 3D printing, and direct metal 3D printing.

Engineers in BMW AG’s jigs and fixtures department in Germany discovered that 3D printing allowed them to create ergonomic hand-held assembly devices for the factory floor that were superior in performance to conventional metal-cutting manufacturing methods (Stratasys, 2015). The 3D printed assembly enhanced productivity, worker comfort, ease-of-use, and process repeatability all thanks to greater design flexibility made possible with AM. In one instance, BMW engineers reduced the weight of a hand-held assembly aid by 72% by replacing the solid-fill of the tool’s core with internal ribs, removing 1.3 kg (2.9 lbs). Although this reduction may appear marginal, it can have a dramatic impact on assembly workers who rely on the tool, using its hundreds of times in a single day (Stratasys, 2015).

The organic designs enabled by 3D printing can increase manufacturing efficiency and productivity by improving the handling characteristics of manufacturing tools with more sweeping and flowing shapes. In addition to its weight reduction, this particular hand-tool was 58% less expensive to produce than traditional machining methods and was manufactured 92% faster. Engineers at BMW suggested that 3D printing technologies were becoming an increasingly important manufacturing method for low-volume components and that “no enterprise [could] afford to do without rapid prototyping for product development” (Stratasys, 2015, p. 2). As AM technologies evolve and overcome some of their current limitations, the number of opportunities throughout the production cycle where the technologies could be used will only increase.

5.2.2 A Strategic Framework for Additive Manufacturing in the Auto Industry

When analyzing the influence of AM on competitive relationships in the automotive industry, Giffi et al. (2014) identified AM driven product innovation and supply chain transformations as the two area most likely to affect competitiveness and to potentially disrupt or revolutionize the industry. Firstly, by eliminating design restrictions and enhancing manufacturing flexibility, AM could be a significant source of innovation leading to products that are faster, safer, lighter, and more efficient. For instance, automotive parts could be designed with costume features in mind, such as the integration of hollow structures to house electrical wiring. High strength components that are also lightweight can be created with complex structural geometries that were not possible without AM. Materials with favourable properties (e.g., high strength and electrical conductivity) can be built into the layers of a product to enhance functionality using newly developed multi-material 3D printing, further increasing the variety of components that can be produced via AM.

Secondly, AM could have a transformative effect on the structure of supply chains by reducing costs, encouraging simplification, promoting decentralization, and improving market responsiveness through reduced time-to-market (Giffi et al., 2014). Reduced material utilization (an inherent benefit of AM) and the flexibility to design for lightness would drive down logistics costs while on-demand and on-location manufacturing capabilities could support decentralized manufacturing with low-to-medium production volumes—further reducing the cost and complexity of supply chains. Together, product innovation and supply chain restructuring provide AM with the unique ability to transform the ways in which products are designed, developed, manufactured, and distributed (Giffi et al., 2014). The degree to which individual OEMs harness the capabilities available through AM will determine the potential for the technology to drive change within organizations and foster more sustainable, alternative business models.

In their analysis, Giffi et al. (2014) identify four separate tactical pathways with which companies could choose to create value through AM. The potential value of AM, according to the researchers, lies in its ability to break free from two fundamental performance barriers inherent in traditional manufacturing methods. The first trade-off is the relationship between production scale and capital costs. When using AM, economies of scale can be achieved with less capital by lowering the efficient scale of production (the point at which both production output and long-run total average costs are minimized), which has the potential to influence the configuration of supply chains while reducing barriers to entry into mass markets. The second performance trade-off is the relationship between scope and capital. Additive manufacturing is inherently flexible, allowing a variety of differentiated products to be manufactured using the same 3D printing device without any additional cost from production changeovers or customization, a fact that is likely to have a dramatic effect on automotive design. Essentially, additional complexity and short-run production are free with AM.

The pathway that emerges within each individual firm will be co-determined by the extent to which their business strategy prioritizes performance, growth, and innovation and insofar as they choose to deploy the capabilities of AM within their business. Giffi et al. (2014) identified four strategic pathways based on the above performance parameters:

- "Path I (stasis): Companies do not seek radical alterations in either supply chains or products, but may explore AM technologies to improve value delivery for current products within existing supply chains;
- Path II: Companies take advantage of scale economics offered by AM as a potential enabler of supply chain transformation for the products they offer;
- Path III: Companies take advantage of the scope economics offered by AM technologies to achieve new levels of performance or innovation in the products they offer; and
- Path IV: Companies alter both supply chains and products in the pursuit of new business models" (p. 5).

Stasis, the first tactical pathway, emphasizes performance improvements by deploying AM to enhance the efficiency of current operations, as described above with the current uses and applications of AM in the automotive industry. The long-term and far-reaching opportunities for AM in the automotive industry, as shown in path IV of this framework, is the ability to drive both performance and growth through business model evolution using the benefits of AM.

In anticipation of these long-term goals, automotive manufacturers will likely first progress along Path III—product innovation. During this intermediate phase, AM is used to fundamentally alter the product development cycle from the design phase to the assembly phase by reducing the capital intensity required for product innovation and reducing the complexity and cost of vehicle assembly through AM-enabled part simplification and consolidation (Gaffi et al., 2014). As discussed previously, by removing design limitations imposed by traditional manufacturing methods, which proliferates the number of parts required to produce a component and increase the duration and complexity of the assembly process, AM can consolidate parts together, decreasing the time and cost required for assembly while also increasing production quality.

Using lightweight materials (e.g., carbon fiber and aluminum) and complex structural configurations (e.g., lattice structures) automakers can minimize logistics costs and improve the fuel economy ratings of their vehicles. If AM is to foster business model innovation, longer-term strategic imperatives should emphasize performance along with growth and innovation. Path IV denotes significant changes to both product design and supply chains. Additive manufacturing is most competitive at medium-to-low production volumes, supporting a transition to geographically distributed production sites. Decentralization in the automotive industry is likely to have a significant impact on business models, improving their responsiveness to market dynamics and reducing logistics costs through disintermediation to shorten and simplify supply chains. Future business models enabled by AM capabilities and benefiting from economies of scope could emphasize customization which could be used strategically to improve the level of satisfaction consumers derive from a product designed and-or customized specifically for their needs and lifestyle, empowering consumers with a greater sense of control (Gaffi et al., 2014).

5.3 Additive Manufacturing: A Tailwind for Micro-Factory Retailing

The ubiquity of least cost economies of scale in the automotive industry is antithetical to the industry's general ambition of becoming more sustainable. The link between patterns of production and consumption has been discussed as well as the industry's perpetual affliction with overcapacity and massive inventories of unsold vehicles in mature markets like the TRIAD. Apart from its economic challenges, the existing production paradigm is associated with adverse environmental outcomes, including high material utilization and GHG emissions to name a few, that cannot be sustained indefinitely and suggests that a major transformation is inevitable—and possibly imminent. However, automakers are fundamentally bound to this particular *modus operandi* because of the immense capital investments required for manufacturing vehicles with Budd-style all-steel bodies. Maintaining high-level economies of scale with larger production volumes is the primary way in which VMs amortize these costs. Apart from reducing overhead costs from task overlap, the main reason for the automotive industry's long history of consolidation and strategic partnerships was to increase production volumes to achieve even greater economies of scale, which only perpetuates issues of overcapacity and unsustainability. The key to improving sustainability in the automotive industry is to reduce the capital intensity of automotive production to remove the need for economies of scale by replacing the industry's core production technologies.

The potential alternative production system or industrial ecosystem that is being considered in this thesis is the MFR concept, which Wells and Orsato (2005) emphasized "is not just normal car manufacturing on a small scale; it necessarily requires and enables radically new automotive technologies and production processes" (p. 21). A key contention of this thesis is that as AM could soon become a compelling alternative for the industry as it undergoes a major transition towards greater sustainability, away from capital-intensive all-steel car bodies that rely on subtractive manufacturing methods. Presuming that the outcome of a paradigmatic shift in the automotive industry is a structure closely resembling MFR, as this thesis is proposing, AM could be used to facilitate a transition in this direction given that it promotes business model innovation. Likewise, MFR itself provides an opportunity and space for the development of novel technologies, such as AM, since MFR is inconceivable in the context of the industry's existing production paradigm and technologies.

Additive manufacturing could disrupt the manufacturing process, the structure of capital, and the configuration of supply chains in the automotive industry. Lightweight construction and materials would also make cars more efficient and less harmful to the environment. The distinct benefit of AM is its ability to provoke business model innovation. The MFR concept promotes decentralized small-scale manufacturing (for which AM is ideally suited) since it reduces the minimum efficient scale of production and reduces high barriers to entry. Additive manufacturing and MFR are highly complementary and share many of the same goals. A key challenge for AM that could also prevent it from breaking into the mainstream within the current production paradigm is that its primary advantages are present only at low-to-medium production volumes. Additive manufacturing is much less competitive given the high volumes of the current mass production system. Scale is a key differentiator between mass production and MFR, which suggests that not only could AM help facilitate a transition towards MFR, it also necessitates a transition to lower volume production for it to provide a competitive advantage. Therefore, it is feasible for AM and MFR to co-evolve, due to their mutually beneficial relationship throughout the ecological modernization of the automobile industry.

Additive manufacturing could also yield economic benefits for OEMs by reducing the size and complexity of their supply chains and increasing the amount of value they generate by reducing the proportion of value that is outsourced to part and component suppliers. Automakers have continuously sought to reduce the complexity of their supply chains over concerns regarding the time, effort, and money required to manage and plan bulky logistic networks. By bolstering their internal capabilities with AM, OEMs could make a larger value contribution and reduce outsourcing, saving time and money (Giffi et al., 2014). As a result, system integrators or tier 0.5 suppliers would likely retain or increase their level of value creation through R&D and production while simultaneously reducing their involvement in oversized supply chains. Greater value contributions by OEMs would have a negative effect on lower-tier suppliers who stand to lose their share of value creation, likely accelerating future consolidation in the supply network (Giffi et al., 2014).

A potential misalignment between the objectives of AM and MFR is the opportunity to accelerate technological obsolescence, due to shortening production and development cycles with AM. The improved responsiveness and flexibly awarded to VMs with AM technology could potentially induce faster model changes or updates, accelerating the pace of technological obsolescence to encourage increased vehicles sales. Ideally, however, the MFR concept would remove the incentive to increase production to achieve economies of scale, negating the potential for increase obsolescence. Furthermore, AM could also be used to discourage or reduce premature vehicle replacement and prolong vehicle life spans—an important consideration for improving the industry's environmental sustainability. In the context of MFR, AM could reduce the cost of and lead times for replacement parts, helping to reduce the number of vehicles that are deemed "beyond economic repair". Large, expensive inventories of older parts would not have to be maintained since those parts could be produced on-demand or built-to-order with AM. Furthermore, AM could enable more sustainable alternatives to buying a new vehicle such as upgrading or retrofitting an existing vehicle with the latest technology or feature. It is, therefore, important that companies deploy AM in a way that engenders the role of sustainability described in the MFR model.

5.4 Challenges Facing the Adoption of Additive Manufacturing

There are a myriad of potential benefits and opportunities for AM in the automotive industry, including a mutually supportive relationship with MFR. However, there remain challenges that will need to be resolved before AM can truly become a disruptive force. A crucial obstacle with respect to automotive manufacturing is the ability to cost-effectively print larger parts, such as body panels (Giffi et al., 2014). Most commercially available 3D printers cannot accommodate industrial sized parts and components, suggesting a possible need for AM technologies that are developed exclusively for use in automotive manufacturing.

Finish quality and required levels of post-processing must also be addressed before AM can be used reliably for production components. Repeatability is also a concern due to thermal stress and the potential for small air pockets or voids created during the printing process that can affect the consistency and uniformity of quality standards (Giffi et al., 2014). Conventional methods can sometimes outperform AM in terms of dimensional accuracy, which could reduce levels of fit and finish and pose a problem for certain high performance parts and precision components. Post-processing is required in some capacity once a product has been 3D printed to either remove excess material or support structures and to improve surface finish. The quality and reliability of these procedures must be improved to ensure that the finish quality of 3D printed products is as good as or better than traditional manufacturing. A possible solution to overcome these issues is to combine beneficial aspects of additive and subtractive manufacturing. With hybrid manufacturing, the benefits of AM can be maintained while improving finish quality.

Another barrier that has reduced the competitiveness of AM is the higher cost and limited selection of compatible materials. Some novel materials have been developed exclusively for use in 3D printing but their application has so far been limited and costly. However, research into new materials for AM is continuing to gain momentum with the intent of developing high-strength thermoplastics, carbon fibers, and nanomaterials (Giffi et al., 2014). As the breadth of materials amenable to AM increases and as their cost is reduced, material cost and selection could very well become a competitive advantage rather than a barrier.

5.4.1 Multi-Material Additive Manufacturing

A related initiative is to integrate multiple material feedstocks simultaneously to create multifunctional structures or parts without any additional processing or assembly. The emerging technology known as "multi-material additive manufacturing" (or MMAM) would enable variations in material type or composition to be embedded into a product at specified 3D spatial locations. The addition of multiple materials would occur freely and be digitally controlled throughout the printing process (Vaezi, Chianrabutra, Mellor, & Yang, 2013). Performance optimization is a major potential benefit of MMAM; a product's mechanical properties or level of sophistication can be enhanced to improve or increase its functionality. Incorporating specific material properties directly into a product's design would increase design freedom and could enable unique product features and functionalities without increasing costs. For instance, desirable properties such as thermal or electrical conductivity, strength, hardness, and temperature resistance could be incorporated into a product's design to enhance functionality or create entirely new capabilities. Additionally, electronic devices (e.g., resistors, circuits, and sensors) could be embedded directly into a product to conserve space and reduce the product's size (Vaezi et al., 2013).

Part consolidation could increase with MMAM to reduce assembly and labour requirements. Streamlining manufacturing could reduce time, costs, and material and energy inputs resulting in manufacturing that is more efficient and less environmentally taxing. The potential benefits of MMAM offer more than just marginal improvements over conventional manufacturing technologies that are unable to achieve similar levels of material integration. According to Vaezi et al. (2013), MMAM could bring about an entirely new manufacturing paradigm once it becomes cost competitive with existing technologies.

Before MMAM is commercialized, some issues must be resolved. Current challenges include: Contamination between material feeding systems, weak bonds between layers of different material, the CAD file type used for AM cannot specify material composition; delays and process interruptions can occur when using multiple material feeding systems; integrating multiple processes into an efficient hybrid system and developing new capabilities for multi-axis printing; and lastly, developing new materials with specific, desirable properties (Vaezi et al., 2013).

5.4.2 Adding a Fourth Dimension to 3D Printing

Researchers working to develop specialized materials for 3D printing materials have recently delved into the fourth dimension with innovative "smart materials", defined by Khoo et al. (2015) as having the ability to manipulate their shape or some other property in response to an external stimulus. The ability to change over time is regarded as the fourth dimension. The evolution of 4D printing was only recently made possible thanks to three key innovations: (1) advancements in printing technology by Stratasys Ltd with their Connex3 Object500 printer; (2) advancements in metallic 3D printing pioneered by SLM Solutions and their Selective Laser

Melting (SLM) technology; and (3) developments into smart materials and active fibres (Pei, 2014; Khoo et al., 2015). When combined, advancements in these three areas made it possible to create 4D printed components consisting of successive layers of stimuli-responsive adaptive, biomimetic composites or multi-materials with varying embedded properties or functionality that allowed them to transform themselves over time through a physical or chemical change of state based on external stimuli (either natural or induced; Pei 2014).

By sandwiching conventional 3D printing materials like thermoplastics with varying amounts of synthetic smart materials, 4D printed components can be designed with low-level functionality or self-assembly (the process of organizing disordered parts into an organized structure). Smart materials would have the ability to adapt and change over time only when activated by an external stimulus specific to each particular material (Pei, 2014). The presence of water, for instance, could act as a trigger to initiate the self-assembly of components containing layers of absorbent smart material (capable of expanding up to 150% of its original size) within its geometry. Based on the location and the quantity of smart material used, the object would be able to bend and twist itself into the desired shape (Pei, 2014).

Although a more in-depth analysis of 4D printing is beyond the scope of this thesis, it remains important to touch upon the evolutionary nature of AM and a potential future trajectory for the technology that is also relevant to the automotive industry. German automaker BMW recently unveiled a prototype vehicle that it called the "Vision Next 100" to display its foresight into the next 100 years of automotive innovation and mobility. The concept featured BMW's pioneering design philosophy known as "Alive Geometry" which includes dynamic, fully enclosed wheelhouse covers that move harmoniously with steering manoeuvers to optimize the vehicle's aerodynamic efficiency (Seizt, 2016). Essentially, the wheels remain enclosed under steering because the covers stretch in response to tire movements. The innovative, flexible wheelhouse covers offer a new frontier for kinematics, driving performance, and design at BMW and would be manufactured using a 4D printing process that would allow the complex component to be fully manufactured—including its dynamic properties and finished paintwork—in a single step using a single machine, essentially eliminating all material waste from the manufacturing process (BMW, 2016).

Chapter 6 A Review of the Electric Mobility (EM) Literature

The previous chapter detailed current and future opportunities for AM in the automotive industry as well as its potential sustainability benefits. The second proposed technological innovation that could be used to facilitate a transition to MFR is EM. However, before outlining the impacts of an EM ecosystem to the auto industry, this chapter will review the extensive body of literature that focuses on EM. In addition, this chapter will provide a brief history of electric vehicles (EVs), and discuss the environmental benefits of electrification, barriers to the adoption of EVs, and profiles of potential adopters. The chapter will conclude with an examination of government policies and regulations aimed at overcoming adoption barriers and expanding the EV market.

6.1 Types of Electric Vehicles

The literature appears to distinguish between three types of EVs: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). From a driver's perspective, HEVs are the most similar to an internal combustion engine vehicle (ICEV). Generally, hybridization (the addition of a larger battery and an electric motor) is used to provide some additional power to the drivetrain, allowing the ICE engine to be downsized for greater fuel economy[9]. Hybrids cannot be recharged from the electrical grid and tend to have a driving range that is similar to that of ICEVs (e.g., the Toyota Prius & Hyundai Ioniq). As its name suggests, a PHEV is similar to HEV but its battery (which is often larger) can be plugged-into the grid and recharged, providing a relatively short range (20-80 kms) of 100% electric, zero-emission driving. Once the battery is sufficiently depleted, PHEVs recruit an ICE for additional power and operate as an HEV (e.g., Chevy Volt & BMW i8).

The final category of EV and the only type without an ICE are BEVs, also referred to as zero-emission vehicles (ZEVs) because of their 100% electric propulsion (e.g., Nissan Leaf & Tesla Model S). The lack of an ICE means BEVs have the largest battery capacity (offering a range between 100 and 400 kms) and must be plugged into an electrical outlet to be recharged and to restore their full driving range (Axsen, Goldberg, & Bailey, 2015). Due to their greater potential to reduce GHG emissions (a pivotal factor for the future of sustainable mobility), this

[9] Refer to UCS (n.d.b) for a description of the three types of HEVs: series hybrid, parallel hybrid, or series/parallel hybrid.

thesis focuses primarily on PHEVs and BEVs—collectively referred to herein as plug-in electric vehicles (or PEVs).

A new subcategory of EV known as an extended-range battery electric vehicle (or BEVx) was legislated by the California ARB in their 2012 report outlining amendments to their ZEV mandate (Voelcker, 2013). Vehicle's qualifying for this designation must adhere to specific requirements regarding the minimum amount of electric range, the total amount of additional range, and the amount of emissions released (Voelcker, 2013). The distinguishing feature of a BEVx is a small auxiliary power unit (APU) that can provide a limited amount of additional range. The BMW i3, for instance, can be equipped with an optional APU that powers a small generator that maintains a constant minimum charge in the battery once it has been depleted. Often referred to as "range-extenders", APUs are intended to quell range anxiety (a common barrier to BEV adoption) rather than to provide a substantial amount of additional range.

6.2 A Brief History of Electric Vehicles

The history of the electric car closely matches advancements in battery technology and the chemical storage of electrical energy (Høyer, 2007). The technological breakthroughs made during the "golden age" of EV development and deployment between 1880 and 1900 still form the technological basis of today's EVs (Høyer, 2007). The electric car industry continued to thrive after this period because of the circumstances of the First World War, which saw gasoline shortages, the requisitioning of ICEVs for use in the war, and an abundance of electrical energy following the development of both coal-fired and hydro power stations in various European countries. The electric car boom would quickly fade during the 1920s when the electric car began losing significant market share to the increasingly competitive gasoline and diesel powered ICE and would come to a near complete halt in 1929 after the stock market crash that saw most of the remaining electric carmakers collapse in the Depression.

Interest in EVs would re-emerge in the 1960s along with the advent of the modern environmental movement, coinciding with Rachael Carson's acclaimed 1963 novel *Silent Spring*. During this period, environmental pollution was mostly considered a localized problem requiring a local solution. As such, emissions from private automobiles were considered problematic for local air quality and EVs were viewed as a possible solution (Høyer, 2007). Despite a renewed interest in electrification to address local air quality, most of the attempts made to develop an electric car during this period never emerged from the prototyping phase which reinforced existing notions that BEVs would remain inferior to ICEVs in terms of driving range and performance, all the while costing considerably more to purchase in comparison.

A second round of attempted EV commercialization began in the 1970s following three international events that brought the global energy crisis to the vanguard of a public discourse on the environment in most Westernized nations and subsequently reinvigorated an interest in EVs. The first event was the publication of the 1972 book *The Limits to Growth*. The nontechnical report, commissioned by the global think tank Club of Rome, emphasized the absolute global limits of the Earth’s natural systems and their ability to sustain future economic and population growth based on the continued exploitation of non-renewable resources like fossil fuels. Later, it became clear that the earth was also subject to limits on global carbon emissions as natural carbon sinks were found to have a limited ability to take up and sequester atmospheric carbon—highlighting the potential threat of increasing concentrations of atmospheric CO_2 and the GHG effect. Coinciding with this newfound consciousness of environmental limits to growth and carbon sequestration was the Arab oil embargo (1973-1974) which prompted extensive rationing in the US as prices surged with the drop in supply. This event in particular brought the energy crisis to light and sparked a public debate over the issue. The third event to draw attention to the world's energy problems as part of the growing public discourse on the environment was, in fact, a series of events that lead to a heightened distrust and debate over the use and safety of nuclear energy.

Collectively, these events shone a light on the pressing need to develop alternative, renewable energy resources and technologies like wind, wave, and solar power; bio-energy; and geo-thermal energy (Høyer, 2007). An international effort into researching and developing “soft energy paths”—the term coined by Amory Lovins (1977) for alternative energy scenarios based on renewable resources—began in response to the public debate on the energy crisis. Alongside these efforts was a renewed attempt by large OEMs from Japan, Europe, and the US to develop EV technologies, which were now considered a prospect not only for emissions free transport but also as a means of bringing energy independence to the US by utilizing clean, renewable energy resources that could be developed domestically and allow the US to quell its demand for foreign oil imports (Høyer, 2007). A sign of this renewed focus was the “Electric and Hybrid Vehicle

Act of 1976" passed by the US Congress to promote R&D as well as demonstrations of EV technologies with the express purpose of electrifying the entire US automotive fleet by the turn of the Millennium. Despite the ample interest and activity in and around the development of EVs during this period, not a single EV was successfully commercialized and the end of the decade most, if not all, EV development activities were quashed (Høyer, 2007).

It would not be long however before EVs re-emerged within the public consciousness as a result of growing concern over deteriorating air quality, specifically within large metropolitan areas. In 1990 for instance, the California ARB implemented a fervent regulatory initiative to improve air quality that included unprecedented legislation requiring the development and sale of zero-emission vehicles (ZEVs) by global automakers operating in the state. This momentous political decision was taken mainly in response to the increasing concentration of cars and air pollutants in metropolitan Los Angeles (Høyer, 2007). Throughout the 1960s and 70s, transport problems were most often viewed as problems of intensity (i.e., too many cars concentrated in one area resulting in poor local air quality). However, unlike other sectors that have stabilized or even reduced their energy use during the post-industrial period, energy use for passenger and freight transport has continued to increase despite countervailing measures to reduce GHG emissions from personal transport especially. This is due in part to the transport sector's pronounced volume growth and its inextricable linkage to the fossil fuel industry.

An appreciation of this relationship led to an important shift, beginning in the 1990s, in how transport problems were viewed. Instead of being billed as problems of intensity, they were increasingly seen as problems of volume (i.e., too many cars generally consuming too much fossil fuel energy contributing to macro-level pollution both regionally and globally including climate change). This new framework for understanding transport problems lead to the development of two new concepts used extensively in academic and public policy realms in regards to sustainability. The first was *sustainable transport*, which focused more so on the physical means of transportation and the infrastructure it makes use of; and the second was *sustainable mobility*, which broadened its view by taking into account the wider social patterns and volumes associated with the movement of people and freight. However, both concepts were unanimous in their position that EVs are a major prerequisite for sustainability at all scales from local to global (Høyer, 2007).

The history of the HEV is nearly as long as the history of the BEV with which it is tightly intertwined. (Refer to sections eight through ten in Høyer (2007) for a detailed account of this history and a description of the various types of HEVs.) In short, HEVs were first developed as a solution to the limitations of BEVs and were mostly pioneered by small companies and even some do-it-yourself (DIY) backyard engineers. A fundamental benefit of the HEV configuration is that it avoids the large, heavy, and costly battery packs required by BEVs in favour of an electric motor designed to assist the ICE, which can be downsized by as much as 60% as a result. In a similar fashion as BEVs, hybrids originally failed to re-emerge during the energy crisis, unable to make it passed the prototyping phase, despite legislation like the aforementioned *Electric and Hybrid Vehicle Act* and initiatives like the 1993 *Partnership for a New Generation of Vehicles* (PNGV). Even with the ARBs ZEV legislation, which came into effect in 1996, annual sales of BEV did not surpass 1000 units globally between 1995 and 2000 (Dijk & Yarime, 2010). Despite their dismal success, Toyota saw a business opportunity for its hybrid technology, which it had advanced in the wake of the ZEV legislation, despite the automotive industry's successful campaign to have some of the legislation repealed (Dijk & Yarime, 2010). Toyota first commercialized its Prius hybrid in 1997 in its home market of Japan. The Prius arrived in the US, initially only in the state of California, for its second generation in 2000. Toyota's Japanese rival, Honda was the first to offer a HEV in the US with the launch of its two-door Insight in California in 1999. Unlike the Insight, the Prius proved more successful than anticipated, winning "Car of the Year" from US magazine *Motor Trend* and the North American International Auto Show in 2004—the year of its global debut—despite its initial premium price tag over comparably sized ICEVs (Høyer, 2007).

Overall, the history of EV development can be characterized by many vicissitudes. While changing social contexts lead the charge for their development several times over, fundamental barriers such as purchase price, driving range, top speed, and charging time seemed to consistently act as a barrier to their widespread development and adoption (Høyer, 2007). A second era of HEV development was spearheaded by Toyota's Prius, which experienced some level of acceptance on the global market, though it was the only HEV to do so. Moving forward however, it appears that newly developed PHEVs and BEVs will likely overtake much of the existing HEV market share due to their higher emissions reduction potential.

6.3 Quantifying the Environmental Impact of Electric Vehicles

Plug-in electric vehicles offer several distinct advantages over conventional ICE vehicles including improved powertrain efficiency, fewer moving parts requiring less frequent maintenance, and zero tailpipe emissions during all-electric driving which helps mitigate the effects of climate change and urban air pollution (Hawkins, Gausen, & Strømman, 2012). However, there remains a negative perception—mostly among non-adopters—that BEVs are not indeed more environmental friendly than ICEVs due to the indirect GHG emissions resulting from generating electricity from non-renewable sources to powers PEVs. Many studies have attempted to quantify the environmental benefits of PEVs by comparing their impact to that of conventionally powered ICEVs.

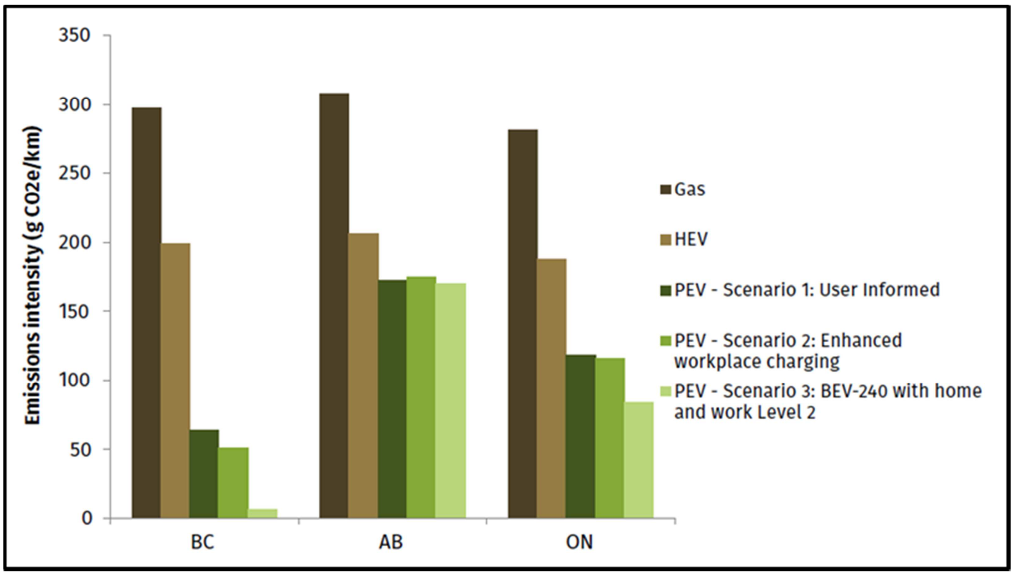

Figure 1 A comparison of well-to-wheel emissions intensity (gCO2e/km) using hourly marginal emissions factors for electricity in three Canadian Provinces based on three consumer-informed PEV scenarios (Axsen et al., 2015, p. 153).

One such study by Axsen et al. (2015) estimated the potential well-to-wheel[10] GHG impacts of PEV use among Early Mainstream[11] buyers in three Canadian Provinces using current electrical generation profiles: British Columbia (hydro-based grid), Alberta (fossil-fuel based grid), and Ontario (mixed grid). The results (Figure 1) use hourly marginal emissions factors

[10] A well-to-wheel analysis comprises life cycle GHG emissions from fuel production and transport (i.e., well-to-tank) and fuel use (i.e., tank-to-wheel).

[11] Data for this analysis was obtained from the 2013 New Vehicle Owners Survey of mainstream Canadian consumers, excluding Québec.

(kg/MWh) for each region to reflect time of use charging and suggest that the GHG intensity[12] of driving a PEV can reduce GHG emissions by 79% in British Columbia (BC), 44% in Alberta, and 58% in Ontario assuming existing recharge access or "user informed[13]" charging, the most likely near-term usage scenario. These results indicate that PEV use can reduce fleet-average GHG emissions intensity compared to HEVs and gas powered ICEVs in all three provinces, despite varying electrical generation profiles. Reductions in Alberta were modest however, reflecting the importance of policy initiatives to increasing the proportion of electrical generations from renewable sources.

The above study considered only well-to-wheel GHG emissions, which excludes emission sources from the rest of the vehicle life cycle including production and disposal. A fundamental tool in IE known as the life cycle assessment (LCA) can be used as a framework for determining the full environmental impact and global warming potential (GWP) of PEVs across their entire life cycle. Nealer & Hendrickson (2015) conducted a comprehensive review of recent LCAs of energy and GHG emissions for EVs and found that the literature unanimously supports the position that EVs have the capacity to reduce GHG emissions when compared to conventional gasoline vehicles. The majority of the energy use and GHG emissions produced by PEVs occur within the use-phase of their life cycle, which is most affected by the electricity mix, vehicle lifetime, vehicle weight, and driving behaviour. As such, it is important that policy initiatives aimed at increasing PEV adoption are matched with realistic goals and timelines for renewable energy investments to improve the GWP of the electrical grid and avoid shifting emissions from one area to another (i.e., problem shifting). The promotion of BEVs in in the absence of such considerations could prove counter to short- and medium-term goals to reduce GHG emissions (Hawkins et al., 2013).

Besides well-to-wheel emissions, both Hawkins et al. (2013) and Nealer et al. (2015) noted the importance of including the environmental impacts of vehicle production when comparing the emission reduction potential of PEVs and ICEVs. Due to the chemical compounds and rare earth metals used in vehicle batteries, the production phase of PEVs tends to be

[12] Measured in grams CO_2 equivalent per kilometre (gCO_2e/km)
[13] See Axsen et al. (2015) section 12.2 (p. 143) for a detailed summary of the three usage scenarios included in the results of emissions intensity of PEVs.

substantially more environmentally damaging than that of ICEVs. Hawkins et al. (2013) found that the GWP of BEV production was about twice that of ICEVs, with battery production accounting for 35 to 41% of the total. Nearly half of the life cycle GHG emissions generated by the base case BEV in the analysis stemmed from the production phase and its associated supply chains. This estimate of GWP for BEVs, however, was nearly twice that of estimates found by previous studies by Baptista et al., 2010; Burnham et al., 2006; Notter et al., 2010; and Samaras & Meisterling, 2008. The authors attributed this discrepancy to their higher estimate of battery-related impacts and the inclusion of other electronic components not inventoried in the other studies. The researchers called on battery manufacturers to make primary inventory data around battery production more publicly accessible to enhance the accuracy of future "cradle-to-grave[14]" analyses by limiting the number of assumptions made regarding the energy requirements and system boundaries of battery production. Hawkin et al. (2012) also advocated for stricter life cycle management and life cycle auditing to limit potential problem shifting, primarily from material requirements for battery production, and to inventory all potential environmental trade-offs associated with the use of BEVs.

Additional IE strategies, such as material flow analysis and design for the environment and for disassembly should be used to identify, evaluate, and reduce or eliminate secondary environmental impacts of PEV production and promote the use of alternative materials and processes to improve component recyclability while reducing life cycle emissions. Nealer and Hendrickson (2015) agreed that the LCA provides a useful framework to estimate and track the GHG emissions of PEVs as they become more widespread, to ensure continued improvements by way of technological advances, including further research on the environmental impact of battery manufacturing, improving EOL battery recyclability, and identifying second-life opportunities for batteries no longer useful in PEVs.

Sensitivity analysis by Hawkins et al. (2012) to test the robustness of their study's results against changes in various base parameters suggested that assumptions regarding battery mass, vehicle lifetime, vehicle efficiency, and electricity mix have the greatest impact on the GWP of the different vehicles type. Important in the context of this thesis is the impact of increasing the

[14] Refers to the full product life cycle including the manufacturing of a product and its input materials to its eventual disposal and reuse.

useful lifespan of vehicles, which has a far greater effect on per kilometer GWP of BEVs than it does for ICEVs due to their higher in-use emissions. This suggests that extending the useful lifespan of BEVs—through upgrading or retrofitting, as suggested in the MFR concept—may have a significant impact on the GWP of PEVs and the overall sustainability of the automotive industry.

6.4 Challenges Facing Consumer Acceptance of Electric Vehicles

Automotive manufacturers and other private sector industries have been racing to develop the next big innovation in battery technology to make PEVs competitive with ICEVs in mainstream markets. Energy storage and density remain the primary barriers for battery manufacturers. A battery's energy storage determines the total distance or range that a PEV can travel on a single charge, whereas a battery's energy density determines its mass and overall efficiency (Egbue & Long, 2012). These issues have been a fundamental problem for EV penetration since their inception and contributed to their initial decline following the introduction of the ICE (Høyer, 2007).

Although these technological hurdles are significant, they are not the only factors that affect consumer acceptance and adoption of PEVs. Social, political, and economic barriers can be equally important. Auto manufacturers and policy makers must be aware of the prevailing social connotations surrounding PEVs if they want to increase consumer acceptance and market share as social barriers can indirectly affect the impetus and direction of technological pathways by influencing the perceptions of new car buyers, as well as society's support (or lack thereof) for regulatory measures that promote the use of alternative technologies (Dikj & Yarime, 2010). This suggests that a socio-technical perspective to identifying deterrents of PEV adoption may be most appropriate and fruitful as it encompasses not only technological barriers but also social, cultural, political, economic, and institutional impediments that can affect consumer attitudes and perceptions towards technological innovations and consumer's willingness to pay (Sovacool & Hirsh, 2009).

Even though it is important for both technological and social barriers to be addressed, social barriers can often remain long after technological impediments have been minimized or resolved if consumer skepticism regarding a technology persists (Egbue & Long, 2012). The recent release of more affordable, long-range PEVs, including the Chevy Bolt and Tesla's highly lauded Model 3, is an indication that technological barriers may soon be less of a factor as the utility of PEVs becomes more or less equivalent to that of ICEVs. Determining attitudinal and societal barriers that impact actual PEVs adoption and outlining appropriate polices to diminish their effect will become increasingly important as the technological gap between PEVs and ICEVs narrows.

Addressing barriers to consumer acceptance and adoption of PEVs is imperative as the degree of environmental benefit that society can achieve with ZEVs hinges entirely on their rate of adoption and total market penetration. Significant reductions in CO_2 emission for climate change mitigation will not be possible without widespread acceptance and adoption. Governments hoping to meet emissions targets through GHG reductions in the transport sector will likely need to consider the use of various policy and regulatory measures to overcome barriers to adoption and increase market share. For instance, data retrieved from the Government of Canada (2017) shows that light duty passenger cars and trucks accounted for roughly 48% of Canada's GHG emissions from the transport sector in 2015 while emissions from freight transport accounted for fewer than 37%.

The innovation literature has suggested that novel technologies diffuse through a series of niche markets—small groups of consumers willing to pay a substantial premium for a technology they perceive to have superior characteristics (Steinhilber, Wells, & Thankappan, 2013). Within these niches, technologies experience gradual improvements allowing them to reach further into the market. Innovative technologies often remain within these niche markets until a critical threshold of users or early adopters is reached, at which point the new technology may be pushed into the broader mass market, beginning the process of a regime transition (Steinhilber et al, 2013). Socio-technical barriers can often impede this process, preventing a transition from a niche market to the mass market. New technologies often require regulatory support as well as continuous technological improvement to meet the demands of both producers and consumers, specifically during the earliest stages of development when cost premiums are typically the highest (Steinhilber et al., 2013). If the factors constraining innovation diffusion are not properly understood and addressed, a technology with superior characteristics can still fail to reach mass-market acceptance. Below is a review of potential barriers affecting consumer acceptance and adoption of PEVs.

Coffman, Bernstein & Wee (2017) conducted a comprehensive review of 50 peer-reviewed studies that considered key factors affecting the rate of EV adoption given the recent jump in commercially available PEVs. The review distinguishes between internal (i.e., vehicle properties) and external (i.e., societal contexts) factors affecting PEV adoption. Purchase price, driving range, and recharge time were the primary internal factors cited in the literature. The higher initial purchase price of PEVs relative to ICEVs has been cited as a significant barrier (Carley et al., 2013; Graham-Rowe et al., 2012; Lebeau et al., 2012). The limited driving range of BEVs has also been highlighted; consumers have often assigned a significant value to additional driving range (Carley et al., 2013; Egbue & Long, 2012; Hidrue et al., 2011; Hackbarth & Madlener, 2013). Finally, minimizing recharging time has received high valuations by potential PEV consumers surveyed by researchers (Graham-Rowe et al., 2012; Hackbarth & Madlener, 2013; Hidrue et al., 2011).

Due to consumers' apparent emphasis on driving range, several studies have suggested that consumer preference for PHEVs is greater than for BEVs due to their superior range (Carley et al., 2013; Axsen & Kurani, 2013; Tamor, Gearhart, & Soto, 2013). Conversely, when attempting to determine adequate levels of charging infrastructure, Tran et al. (2013) found that consumer preference for BEVs was higher than for PHEVs and concluded that range anxiety was best addressed through increased access to public charging rather than through increased single-charge driving range. Similarly, Graham-Rowe et al. (2012) found that willingness to pay for extended range was higher when fast charging was unavailable. Clearly, important relationships exist between internal factors (i.e., range and charging time) and external factors (i.e., access to charging infrastructure) and more research is needed to determine the implications of these factors and their relationship on vehicle usage and adoption (Coffman et al., 2017).

The primary external factors identified by Coffman et al. (2016) affecting actual or intended PEV adoption were the impact of fuel prices on the Total Cost of Ownership (TCO) of PEVs compared to ICEVs and HEVs (Al-Alawi & Bradley, 2013; Prud'homme & Koning, 2012; Tseng et al., 2013; Wu et al., 2014); the potential influence of different consumer characteristics and socio-economic factors; the effect of access to and availability of charging infrastructure (Bakker, Maat, & Wee, 2014; Cambell, Ryley, & Thring, 2012; Egbue & Long, 2012; Schroeder & Traber, 2012; Lopes, Moura, & Martinez, 2014; Sierzchula et al., 2014; Mersky, Sprei, Samaras, & Qian, 2016); the influence of PEV awareness and visibility (Mau, Eyzaguirre, Jaccard, Collins-Dodd, & Tidemann, 2008; Axsen, Mountain, & Jaccard, 2009; Axsen & Kurani, 2013); and the impact of social norms (Lane & Potter, 2007; Eppstein, Grover, Marshall, & Rizzo, 2011; Axsen & Kurani, 2013; Burgess et al., 2013; Mohamed, Higgins, Ferguson, & Kanaroglou, 2016).

The only study to look at the impact of relative fuel prices on actual PEV adoption was a study by Sierzchula, Bakker, Matt, and Wee (2014) who found that fuel prices were not a strong predictor of PEV market penetration. On the other hand, Coffman et al. (2016) noted that this finding contrasts somewhat with other studies looking at consumer uptake of HEVs and found that relative fuel prices were a strong predictor of market uptake (Beresteanu & Li, 2011; Diamond, 2009; Gallagher & Muehlegger, 2001). This suggests the impact of fuel prices on PEV adoption is a potential area of future research.

6.5 Who is Most Likely to Adopt an Electric Vehicle?

There is a plethora of research on the potential impact of various consumer characteristics on one's likelihood of purchasing a PEV. This information is often used to predict future rates of PEV adoption or to segment the population into discrete groups with varying rates and likelihood of PEV adoption (e.g., early adopters vs. laggards). Indicators that were commonly used among the studies reviewed by Coffman et al. (2016) to characterize consumers' interest in PEVs were level of education, income, number and type of existing vehicles, concern for the environment, and level of enthusiasm for new or innovative technologies. However, the review offered few concrete conclusions regarding the effect of each indicator on the consumer purchasing preferences and adoption of PEV given that the evidence was fairly mixed with regards to both their level of and direction of influence.

It should also be noted that due to the novelty and limited market penetration of PEVs, most research into these characteristics and attitudes of PEV is based on stated preferences (i.e., a consumer's intention to purchase a PEV) rather than on revealed preference (i.e., actual consumer behaviours). This is important because the literature has also concluded that, in general, consumers are unfamiliar with the features and characteristics of PEVs and the attributes distinguishing PHEVs and BEVs (Morton, Schuitema, & Anable, 2011). Therefore, in the absence of direct experience with a PEVs, consumers are being asked to state their interest in or their intention to purchase a product with which they potentially have little knowledge or experience, resulting in inaccurate or based assessments due to bias the value/attitudinal-action gap (the difference between what people say they will do vs. what people actually do). Unfortunately, due to low PEV market share in most jurisdictions, stated preference is at present the only effective method of conducting this type of research and remains a well-known and widely applied research methodology in the field of EM research.

Another criticism is that such studies often assumes that consumer preferences remain static over time when in reality, the hierarchy of vehicle features and attributes desired by a potential buyer can shift throughout the purchasing process itself. Future research will not only have to account for variation in consumer preferences over time but will also have to determine the potential impact that increased PEV adoption will have on consumer attitudes and perceptions as a result of social learning and through increased marketing, education, and direct/indirect exposure to PEVs (Morton et al, 2011).

6.5.1 Socio-Economic and Demographic Characteristics

Recent work by Mohamed et al. (2016) identified likely PEV adopters in Canada using a stated preference survey of Canadian households who expressed a future interest in purchasing an economy car. The researchers found that younger households were more likely to express interest in purchasing a PEV, in line with previous findings by Hirdue, Parsons, Kempton, and Gardner (2011) and Ziegler (2012). A higher level of education also tends to be associated with a greater propensity to purchase a PEV (Carley et al., 2013; Hackbarth & Medlener, 2013; Hidrue et al., 2011; Mohamed et al., 2016) as does full time employment (Mohamed et al., 2016; Plöts, Schneider, Globisch, & Dütschke, 2014). Having a place to install a home charger, such as a garage, appears to increase consumers' stated preferences for PEVs (Hidrue et al., 2011; Mohamed et al., 2016; Plöts et al., 2014) and was associated with a sense of autonomy among respondents with experience using a PEV (Graham-Rowe et al., 2012). While Hidrue et al. (2011), found that owning multiple vehicles was not important to BEV adoption, Jensen, Cherchi, de Dios, and Ortuzar (2014) found that multi-vehicle households expressed a greater interest in purchasing a BEV both before and after being given experience with a BEV as compared to single-vehicle households. Similarly, Mohamed et al. (2016) and Schuitema, Anable, Skippon, and Kinnear (2013) demonstrated that PEVs were more suitable as a second vehicle rather than as a household's primary vehicle, given their range limitation.

Interestingly, several studies have shown that income level is not a significant factor in determining interest in PEV adoption despite consumers often being aware of their higher initial purchase price (Carley et al., 2013; Hidrue et al., 2011; Mohamed et al., 2016; Sierzchula et al., 2014). Conversely, profiles of American consumers most likely to purchase an EV (i.e., early adopters) were found to be high income individuals with an average annual household income (HHI) in excess of $200,000 while the next group of likely adopters (i.e., early majority) were found to have an above average HHI averaging $114,000 (Giffi, Gardner, Hill, & Hasegawa, 2010). The profile of non-adopters had an average annual HHI of only $54,000. It should be noted that Mohamed et al. (2016) concluded that even significant personal socio-economic and demographic variables have a much smaller impact on PEV adoption than individual attitudes and norms, environmental concern, and perceptions and feelings of technological factors relating to PEV use.

6.5.2 Level of Environmentalism

As a potential solution to transport related emissions of GHGs and other airborne pollutants, driving a PEV is often regarded as a pro-environmental behaviour. Analyses attempting to predict patterns of PEV adoption or understand consumer purchasing decisions for PEVs often include data on consumer attitudes, values, and beliefs towards environmental issues (Rezvani, Jansson, & Bodin, 2015). However, Coffman et al. (2017) found mixed evidence within the literature as to whether or not consumers' pro-environmental beliefs translate into greater likelihood of adoption and, if so, how much of an impact this variable has. They also concluded that a variety of different—often loose—notions relating to levels of environmentalism were used to characterize consumers, potentially contributing to the variance found in the results.

For instance, Skippon & Garwood, 2011 found that most study participants seemed to be aware of the environmental benefits of PEVs, though not all of them linked these benefits to a reduction in GHG emissions. Personal concern for the environment was one of two distinguishing factors among the four attitudinal clusters obtained using cluster analysis. The authors concluded that although the environmental benefits would appeal to some, other participants had not considered BEVs to be the one and only solution for the future of low-carbon future personal mobility. Jensen et al. (2013) found that early adopters of three types of alternative fuel vehicles (AFVs) rated fuel efficiency, environmentally friendliness, and the possibility of alternative fuels higher than non-adopters. On the other hand, Sierzchula et al. (2014) found that environmentalism was not a significant predictor of early PEV adoption across 30 countries in 2012. In a study of fleet operators, Sierzchula found that environmental benefits and an organization's green image were secondary to innovativeness and testing out a new technology.

Research by Egbue and Long (2012) assessing the attitudes and perceptions of individuals identified as "technological enthusiasts" found that although a majority (79%) of respondents said they considered sustainability when making a vehicle purchase, many of them expressed uncertainty regarding the environmental sustainability of EV batteries and the electricity used to recharge them with some individuals even perceiving the current environmental performance of PEVs to be inferior to current ICE technologies. This was troubling for the authors who suggested that environmentally minded individuals may not be swayed by regulatory measures or incentives aimed at increasing EV adoption if they are skeptical of the environmental benefits of PEVs or perceive their use as replacing one problem with another (because of non-renewable electricity generation).

Graham-Rowe et al. (2012) gave participants a PEV for seven days before exploring their beliefs and attitudes regarding the technology. They discovered that although some participants felt good about driving a PEV because of the environmental benefits, many participants did not, and some even reported driving more as a result of feeling less guilty about driving—a potential rebound effect (Herring & Roy, 2007; Hertwich, 2005). Many participants prioritized the personal utility they derived from a vehicle above any environmental benefits and, similarly to the findings of Egbue & Long (2012), many participants expressed skepticism around the overall carbon footprint of PEVs and questioned whether they were truly a green technology.

6.5.3 Access to Charging Infrastructure

The relationship between PEV adoption and access to charging infrastructure is uncertain. The dilemma is deciding which needs to come first. Does having access to adequate[15] charging infrastructure encourage adoption, or is it necessary to reach a minimum threshold of early adopters to rationalize investments in charging infrastructure (Coffman et al., 2017)? However, just like the chicken and the egg conundrum, the relationship can develop into a sort of causality dilemma given that a lack of adequate charging infrastructure has been linked to lower PEV uptake which suggests that governments will likely have to play a pivotal role in not only encouraging early adopters of PEV with favourable policies and incentives but will also need to make the initial investments into creating a public charging network. Coffman et al. (2017) cited driving distance, vehicle range, trip type and duration, home charging, charging time, and grid impacts resulting from charging to be important determinants of what is optimal in terms of the type and distribution of charging infrastructure within the literature.

6.5.4 Social and Behavioural Norms

Mohamed et al. (2016) applied a structural equation model to test a hypothetical, extended version of the Theory of Planned Behaviour (TPB) to determine factors that influence the stated preferences of Canadian households (likely to purchase a new economy class vehicle in the future) towards PEVs. The TPB, as it was originally conceived, predicts how the following three constructs affect one's intention of performing a particular behaviour: (1) attitudes towards the behaviour, defined as the beliefs and evaluations regarding the perceived consequences of performing a behaviour; (2) subjective norms, defined as the perceived pressure from a reference group within society or significant others to engage in a behaviour; and (3) perceived behavioural control, which is determined by one's own judgement of how easy or difficult the behaviour is to perform (control beliefs) and one's expectation of being able to perform the behaviour successfully. The authors added two additional constructs (both of which were cited in the literature to significantly influence PEV adoption behaviour) to the TPB to improve their analysis: (4) concern for the environment and (5) personal moral norms, defined as one's perceived obligation to perform a specific behaviour (i.e., purchasing a PEV). Survey

[15] Refer to Coffman et al. (2016) for a review of what is "adequate" vis-à-vis charging infrastructure.

respondents' behavioural intentions along these five constructs was determined using 18 attitudinal statements based on a five point Likert scale of agreement.

The study's results indicate that respondents' stated intention of adopting a PEV was primarily influenced by one's perceived behavioural control, which was mainly informed by the car's battery warranty and perceived ease of maintaining and operating a PEV; and attitudes towards purchasing a PEV, which was primarily informed by one's perception of a PEV's cost effectiveness (Mohamed et al., 2016). These results indicate that technological factors (e.g., driving range, maintenance, and battery performance) are critical to PEV adoption. Personal moral norms and subjective norms were also found to be significant but to a lesser degree than the vehicle's characteristics. Interestingly, self-reported levels of environmental concern were shown to have a significant indirect impact on the four other behavioural constructs in the analysis, but was not found to be a significant determinant of individual's actual purchasing intentions. This suggests that the impact of an individual's level of environmentalism on PEV adoption is more nuanced, affecting individuals' personal beliefs regarding their attitudes towards and perceived control over PEV use (Mohamed et al., 2016). The authors suggested that additional research like this be conducted in the future, given that late adopters may be influenced by a different set of beliefs, motivations, and social/moral norms than the early adopters profiled in their research, which represented only a snapshot in time of the Canadian automotive market for a particular class of vehicle.

Rezvani et al. (2015) analyzed 16 peer-reviewed studies to identify both drivers of and barriers to PEV adoption. The authors identified and reviewed five different theoretical frameworks used in the literature to identify and understand consumer purchasing intentions and adoption behaviour with respect to PEVs. The predictors of PEV adoption intentions and actual adoption outcomes were categorized into five sub-sections that relate to each of the theoretical frameworks identified. Consumer intentions and actual adoption patterns were found to be affected by various attitudinal factors: a pro-environmental behaviour, a pro-innovation and technology behaviour, a symbolic behaviour, and an emotional behaviour. Attitudinal factors identified in the review were categorized into three separate groups consisting of technical factors (i.e., consumer attitudes and perceptions of PEV range, performance, safety, size, and style), cost factors (i.e., attitudes and perceptions of PEV ownership and operational costs), and contextual factors (i.e., consumer attitudes and perceptions of pro-PEV policies and regulations, and the way in which these policies are framed and contextualized).

With regards to exhibiting a "pro-environmental" behaviour, their review was in line the aforementioned findings on the level of environmentalism discussed in the consumer characteristics section. In short, explanatory studies on the matter are mixed. Pro-environmental values, beliefs, attitudes, and norms are shown to positively affect the adoption intentions of some consumers while others were either unaware or skeptical of the benefits and/or impacts of PEVs on the environment. A critical concept in this regard is the attitude-action gap, in which positive attitudes about a specific behaviour may not consistently result in adoption of that behaviour. Research looking at how to close this gap suggests enhancing consumers' self-efficacy (feelings around their ability to personally make a difference) and exploring the effect of different contextual factors, such as policies and educational framing, on consumer self-efficacy.

Rezvani et al. (2015) found in their review of the literature that as an innovative technology, PEV adoption could improve if their compatibility with consumers' everyday lives and existing habits were improved. Greater compatibility could be achieved with improvements in suitable charging infrastructure and how manufacturers or companies deliver the technology to consumers, separating battery ownership from car ownership is one such example from the literature. On the reverse side, some consumers may be worry about the pace of innovation and technological development, fearing technological obsolescence and waiting for current barriers to be resolved. For instance, as battery performance improves, consumers may worry that future PEVs will offer longer driving ranges and/or shorter charging times. This could potentially encourage some consumers to delay purchasing a PEV.

Consumers often place symbolic meanings or values on products as a means to express their personal identity or social positioning yet, to date, studies have not explored this aspect of PEV ownership (Morton et al., 2011). Rezvani et al. (2015) noted that current research on the symbolic meaning of PEVs and their effect on self-identity tends to be restricted to pro-environmental and pro-technology/innovation expressions. Future research should aim to understand the symbolic meanings placed on PEVs and the desired self-identities of potential adopters as well as their impacts on consumer's purchasing intentions. Differences in symbolic meanings and/or self-identities could arise between countries or technologies (i.e., BEV vs.

PHEV). Desirability bias among survey respondents can pose a challenge when attempting to uncover hidden symbolic meanings, suggesting such information must be obtained through indirect questions to limit potential biases (Rezvani et al., 2015).

Emotional impacts on consumer's attitudes and purchasing intentions were found to be the most overlooked and least researched topics within the PEV adoption literature (Rezvani et al., 2015). Hedonic attributes of PEV use could be an area of future investigation as well as the precursors to and outcomes of these emotions and their impact on PEV adoption. This information could prove invaluable for PEV marketing and educational, and policy initiatives to increasing adoption. Similarly, Morton et al. (2011) determined in their review of the literature that impulsive and unconscious socio-physiological factors, such as emotions, identity, symbolism, and personality, should be included in future research that aims to adequately model car choice among potential consumers.

6.6 Policies and Regulations to Support Widespread Adoption

In their review, Coffman et al. (2017) categorized policy measures used to support PEV adoption as financial and non-financial (use-based) incentives, increasing availability to charging infrastructure, and increasing public education and awareness. The first category includes government subsidies on new PEV purchases or tax rebates on vehicle registration fees as well as other benefits for PEV drivers: reduced or eliminated fees for road tolls or congestion charges, unrestricted access to high occupancy vehicle (HOV) lanes, high occupancy toll (HOT) lanes and/or bus lanes, and free or preferred public parking. While vehicle subsidies address the higher fixed costs of PEVs, namely their higher initial purchase price, use-based incentives decrease the marginal costs of driving a PEV.

Langbroek, Franklin, & Susilo (2016) conducted a stated choice experiment to uncover consumers' perspectives on incentive policies for PEVs. In this particular study, free parking was found to be the most highly valued incentive, higher than current PEV subsidies in Sweden. Free charging was the second most valued while access to bus lanes, though still significant, was valued lower. When combined, the value assigned to these three use-based incentives was equivalent to more than €10,000. The authors also determined that consumers considered to be at a more advanced stage of behavioural change towards PEV adoption (meaning they have a higher intrinsic motivation to adopt a PEV) had a lower price sensitivity and were therefore more likely to adopt a PEV in the future. Survey respondents were grouped into stages of behavioural change based on socio-economic characteristics and socio-cognitive constructs including knowledge of PEVs, attitudes towards PEVs, and level of self-efficacy. The researchers concluded that, perhaps, policy makers should focus on advancing individuals further along these stages of behavioural change through education and increased awareness of the advantages of PEVs so that less extensive, more affordable incentive packages could be designed to target these individuals specifically.

While there is existing literature on consumer perspectives of PEV-supportive policies, Coffman et al. (2017) noted a dearth of empirical research on whether or not existing incentives actually increase PEV uptake. Limited data on the nascent PEV market was hypothesized to be a contributing factor to this lack of information. They concluded that the literature on the impact of PEV incentives is mixed but noted that the magnitude and type of incentives offered are significant. For instance, Sierzchula et al. (2014) found that financial incentives (greater than $2,000) and increased charging infrastructure were both positively correlated with PEV uptake across 30 different countries, but cautioned that this does not necessarily demonstrate a causal relationship between policy and uptake. Increased charging infrastructure was a stronger predictor of PEV adoption than financial incentives but the policies are highly complementary. It was suggested that other underlying factors likely influenced adoption in some countries and that such factors should not be overlooked. Charging infrastructure appears to be important to PEV market share, but the literature has yet to sort out the direction of causality between the two (Coffman et al., 2017).

As previously discussed, the literature has shown that potential consumers are often misinformed or unaware of the potential benefits of PEVs and their characteristics. The literature has also shown that consumers often lack the knowledge necessary to accurately assess differences in TCO between PEVs and ICEVs. Misinformation or information deficiencies can therefore bias consumers against purchasing a PEV. Governments should therefore invest in initiatives aimed at correcting consumer misconceptions around the maintenance and fuel costs of PEVs to increase adoption (Coffman et al., 2017).

6.6.1 Norway's Progressive Electric Vehicle Policies

Norway is a good example of how government policy can be useful in expanding PEV market share given a favourable environment. The country leads the world with the highest level of PEV market share: In 2016, PEVs accounted for just over 29% of all new vehicles sold (i.e., 15.7% from BEVs and 13.4% from PHEVs; EAFO, n.d.). Among the country's total vehicle fleet, PEVs accounted for 2.8% in 2015 (Figenbaum, 2016). Norway's generous incentive program began in 1990, but has developed over time to include additional incentives and became entrenched in Norway's official climate change strategy in 2012. Below is a breakdown of Norway's PEV incentives and the year in which each policy took effect (Haugnland, Bu, & Hauge, 2016):

Financial Incentives

- Purchase/import tax exemption – 1990
- Lowered annual road tax – 1996
- Company car taxes reduced to half – 2000
- Exemption from the 25% Value added Tax (VAT) (Note: equivalent to a goods and services tax [GST] in Canada) on the purchase – 2001 or lease – 2015 of a new PEV

Use-based Incentives

- Exempt from road tolls – 1997, and ferry tolls – 2009
- Free municipal parking – 1999
- Access to bus-only lanes – 2005

Due to the growing market share of PEVs across the country, control over use-based incentives was placed under the jurisdiction of municipal governments as of 2017 and are now subject to change. Road and ferry tolls will also likely be switched to a pricing scheme that is based on CO_2 and NO_x emissions. Financial incentives will remain unchanged until 2018, when they will be revised and phased out over time as PEV market share reaches a critical threshold and so-called "neighbourhood effects" begin to take hold through increased awareness and word of mouth from existing PEV owners (Haugneland et al., 2016).

Figenbaum (2016) analyzed the PEV market in Norway and the factors leading to their success using the Multi-level Perspective (MLP) transition theory. Despite having generous tax incentives on PEVs since 1990, the PEV market share in Norway did not take off until incumbent mass-market vehicle manufacturers began to offer BEVs with lithium-ion batteries in 2010. The analysis revealed that Norway's incentive program did not become effective until the availability of BEVs increased because of growing international pressures to reduce emissions and advancements in battery technology. It is noteworthy that Norway's PEV incentives remained in place long enough to be impactful but that they continued to develop and improve the environment for PEV adoption over time. Until 2013, Norway's tax subsidies lowered the price disadvantage of BEVs so that they could compete effectively with gasoline and diesel ICEVs. Since then, the same subsidies have provided a cost advantage to BEVs over ICEVs as a result of falling battery costs. The literature has often pointed to the additional costs of PEVs as a significant deterrent for potential adopters. Norway was able to leverage its existing transport tax regime that makes use of high registration taxes for new vehicles, annual taxes on existing vehicles, high fuel taxes, and numerous road tolls to bolster the success of its pro-PEV policies (Figenbaum, 2016). Furthermore, 96% of Norway's electricity comes from hydroelectric dams and is relatively inexpensive, which together with the above context makes widespread PEV adoption a sound political strategy and climate change policy.

Another mounting pressure that favoured PEV adoption was the steady expansion in the number of tolls around city centers and along primary roads in Norway. This expansion helped grow the BEV niche market geographically as well as increase the impact of the incentives over time. The relative success of first generation BEVs in Norway suggests consumers are both willing and able to meet their daily transportation needs given the modest all-electric range of vehicles like the Nissan Leaf and the VW e-Golf, Norway's top-selling PEVs in 2015. The report however did acknowledge that charging infrastructure would be essential to encourage PEV adoption among customers with longer commutes in the future (Figenbaum, 2016).

Despite the apparent success of Norway's PEV policies, naysayers have suggested that the program encourages higher-income households to purchase a second vehicle they may have otherwise foregone. Holtsmark & Skonhoft (2014) suggested that several environmental challenges would result from the increase in multi-vehicle households and stated that as a policy instrument to reduce GHG emissions, the country's EV policy misses the mark. Holtsmark & Skonhoft (2014) go on to say that due to the high cost of PEV incentive programs, government's would be better off purchasing emissions credits through the EU's emission trading system, effectively making Norway carbon neutral. The authors also argued that if the rights to a large number of emissions credits were to be purchased and remain unused that the decrease in supply would cause quota prices to increase, possibly contributing to a technological push towards ZEVs. The main argument is that the enormous cost of PEV subsidies cannot be justified by the emissions savings that are achieved by driving a PEV, suggesting subsidizing PEVs is ineffective at reducing emissions and even counterproductive due to unintended consequences. The authors conclude that Norway should discontinue its incentive program as soon as possible and discourage other countries from emulating the Norwegian model. The solution, they argue, is to restrict car use with more aggressive taxes to limit the many social impacts associated with all types of automobility.

Despite such stark criticism, it can be argued that government subsidies are essential, along with increased availability of PEVs, to induce early adoption by making PEVs cost competitive so that as market share increases, positive consumer interactions through word of mouth and neighbourhood effects can take over once a critical mass of adoption has been achieved (Haughneland et al., 2016). The PEV market share in Norway would have likely not been achieved without having subsidies in place. One only has to look to neighbouring European countries with less generous subsidies (or none at all) to realize the effectiveness of Norway's policy program.

Although it can be argued that Norway's subsidies have been effective in increasing the rate of PEV adoption, it is not yet certain whether this demand will continue to grow once the subsidies are scaled back. Countries around the world will likely be watching to see if Norway is successful in its pursuit to become a leader in PEV technology and continue to grow sales of ZEVs when it begins to wean buyers off the generous incentives that have so far been used to grow the PEV market (Autovista Group, 2017). The current Norwegian government has extended the life of its main PEV tax incentives, originally scheduled to be reduced in 2018, until 2020 (Milne, 2017). The current incentive regime is extremely costly for both national and local governments, which will need to determine an effective means of increasing taxation on PEVs without drastically reducing their demand and still clearly favouring the sale of PEVs over ICEVs. In neighbouring Denmark for instance, sales of PEV fell by over 60% year-over-year in the first quarter of 2017 following their decision to phase out PEV incentives between 2016 and 2020 (Levring, 2017). The government later decided to delay and alter its original plan to phase out PEV incentives, likely after recognizing the sharp decline in PEV sales. Denmark's experience could be a sign that the market is not yet prepared to embrace PEVs in the absence of government incentives and should act as a cautionary tale for other jurisdictions looking at how to effectively reduce current PEVs subsidies.

6.6.2 Pro-Electric Vehicle Policies and Initiatives in Canada

A part of its Climate Change Action Plan (CCAP), the government of Ontario recently enhanced[16] its Electric Vehicle Incentive Program (EVIP), which began in 2010, to make it more affordable for people across the province to adopt a PEV and reduce the province's share of GHG emissions while emphasizing support for ZEVs and BEVs with larger batteries and greater seating capacity (MTO, 2017; Plug 'n Drive, 2017). The rationale for removing caps on incentives for higher priced vehicles was that such vehicles tend to have much greater all-electric ranges and therefore have a greater impact on emissions reductions. The revised EVIP provides eligible BEVs and PHEVs with incentives of \$6,000 - \$14,000 with up to an additional \$1,000 for the purchase and installation of fast-charging equipment for home or work as part of the province's Electric Vehicle Charging Incentive Program.

Ontario's long-term climate change strategy is to reduce GHG emissions by 80% below 1990 levels by 2050 (Ontario, 2015). To ensure progress towards this goal, the province also set a target for 2020 of 15% below 1990 levels and recently added a second intermediate target of 37% below 1990 levels by 2030. Several action areas were outlined in the province's CCAP to ensure compliance with these targets, with transportation as the first sector to be highlighted in the report. Transport accounted for one third of Ontario's total GHG emissions, while road transportation (i.e., cars and trucks) accounted for 70% of this total. Increasing the province's share of PEVs is one of the actions aimed at reducing GHG emissions in the sector. The Province set targets for electric and hydrogen vehicles of five percent of new vehicles sales by 2020 (Ontario, 2016).

[16] A cap limiting incentives to 30% of a vehicle's manufacturer's suggested retail price and a cap of \$3,000 on vehicle's with an MSRP between \$75,000 – \$150,000 were removed (MTO, 2017)

The province intends to achieve this goal by maintaining EVIP through 2020 as well as implementing several other planned programs intended to increase adoption: eliminating the harmonized sales tax (HST) on ZEVs in conjunction with the federal government as early as 2018, establishing a four-year EV charging program with free overnight charging for residential customers as early as 2017, and vehicle rebates for low- and moderate-income households to help them replace older and less fuel-efficient vehicles with new or used PEVs (Ontario, 2016). The province also hopes make charging infrastructure more widely available by investing in charging stations in workplaces, multi-unit residential buildings, and along major transportation corridors; ensuring new homes with a garage are equipped with a 240-volt plug; and requiring new commercial buildings and designated workplaces are equipped with a minimum number of charging spots.

The only other Canadian provinces to offer any sort of PEV incentives are BC and Québec. Québec offers $8,000 for eligible BEVs and PHEVs depending on the energy storage capacity of the vehicle's battery (Québec, 2012). There is also up to $600 in financial assistance available for the purchase and installation of an eligible home charging station. In BC, the government offers incentives of up to $5,000 on eligible PEVs (NCDA, 2017). At the federal level, the Canadian Government recently pledged, as part of its 2016 budget, $62.5 million to support infrastructure projects for AFVs, including PEVs, as part of its commitment to "providing national leadership on climate change" and pursuing economic growth through "investments in green infrastructure, clean technologies and lower-carbon transportation options" (NRCan, 2016).

6.6.3 The Canadian Electric Vehicle Market

Canadians purchased 11,060 new PEVs in 2016, more than ever before (Stevens, 2017). The 2016 sales figures represent a 56% increase over the previous year's sales of 7,072 and more than double the 5,356 PEVs sold in 2014. At the end of 2016, the country's total PEV fleet sat at 29,210 vehicles, but remained highly concentrated within three provinces: Québec – 13,464, Ontario – 9,179, and BC – 5,397. These three provinces are the only Canadian provinces with incentive programs for PEVs in place and accounted for 95% of PEV sales in 2016. Ontario experienced the strongest year-over-year growth in 2016 at 68%, while BC saw more modest year-over-year growth of 38%. Both Québec and BC hit a significant milestone in 2016 with

PEV sales surpassing one percent of their respective annual motor vehicles sales while Ontario's PEV share was only half a percent (Stevens, 2017). Both Ontario and Québec have set provincial targets for PEV adoption in 2020 as part of their plan to reduce GHG emissions but both provinces must experience exponential growth to meet its stated targets on time (Stevens, 2017).

Keeping in mind the above literature review on electric mobility and the current PEV market in Canada, the next chapter will consider the perspective of OEMs in a transition toward electrified transportation as well as discuss the importance of business model innovation in achieving greater PEV market share. Additionally, EM will be discussed as a technological tailwind for MFR as well as the potential synergies that exist between AM and EM in the context of MFR.

Chapter 7 The Role of Electric Mobility in a Future Automotive Ecosystem

7.1 Introduction

The rate of PEV adoption is accelerating in major automotive markets like the US, and increasingly in Europe and China due to a combination of factors including government subsidies, declining battery costs, tightening environmental regulations, increasing investments and commitments by incumbent OEMs, and growing consumer demand; as such, the automotive industry will likely need to undergo a significant transformation (Christensen, Wells, & Cipcigan, 2012; McKerracher et al., 2016). An industrial ecosystem based on EM would bring together utility companies (electricity generators and distributors); downstream oil and gas providers; the existing automotive sector (manufacturing and sales); the public sector including local and municipal authorities; the technology sector (telecommunication providers and digital mapping and information suppliers); infrastructure providers including roadways and parking, and charging stations; new automotive suppliers with expertise in battery technology and electrical systems; and new automotive intermediaries exploring new business models, including new entrants and mobility service providers (Andersen, Mathews, & Rask, 2009).

Electric mobility is poised to create an array of new opportunities and challenges for both new and existing stakeholders of automotive value chains. For instance, utility companies would be essential actors in an EM ecosystem, presented with new opportunities for value creation (e.g., as operators of charging infrastructure) while also potentially facing major challenges from a demand management perspective (i.e., uncontrolled PEV charging could exacerbate demand peaks). Although it creates new challenges for grid operators, PEV charging also represents an opportunity: PEVs can act not only as mobile storage devices, but as mobile generating devices used to feed stored renewable energy back into the grid during peak periods to alleviate demand and possibly mitigate the need for additional generating capacity (Anderson et al., 2009). This type of mutually beneficial arrangement between grid operators and PEV owners is often referred to as a vehicle-to-grid (V2G) integration and represents the next frontier in smart grid management (Anderson et al., 2009). By compensating drivers for the stored energy they feed back into the grid, V2G integration could reduce cost barriers to PEVs by subsidizing their TCO.

Similarly, conventional refueling stations, particularly in metropolitan areas where the initial demand for PEVs is expected to be the greatest, should anticipate slower growth and even reduced demand because of EM. These providers may need to reconsider their primary business model to mitigate such losses, perhaps by installing Level 3 fast charging stations. Increasing access to fast charging would likely positively affect PEV adoption by easing range anxiety in potential consumers, which remains a significant barrier. Notable however is a new generation of long range BEVs that could possibly negate the need for vast networks of public chargers as most private vehicle owners would likely plug-in at home overnight when electricity rates are cheapest. This further complicates the relationship between PEV adoption and charging infrastructure, as it is uncertain if the large investment into a public charging network would have the desired impact and ROI.

Alternatively, public charging infrastructure will likely be pivotal for high utilization PEVs used as part of future mobility trends (e.g., shared mobility, ride hailing and taxi services, and autonomous vehicles), and in urban areas where on-street parking is common (McKerracher et al., 2016). However, until the market share of PEVs is sufficient to justify this type of investment and ensure adequate ROI, it is unlikely that oil and gas providers will want to install charging capacity and explore alternative business models. As such, governments will be required to spearhead the initial push and investment into public charging infrastructure[17,18]. Tesla's exclusive-use network of superchargers, initially designed to enable long distance travel for its owners, is one notable exception of an OEM investing in charging infrastructure.

The use of PEVs necessarily entails a shift—perhaps even a full transformation—in the existing automotive ecosystem to accommodate not only a radical new technology, but also a new network of connections, partnerships, and interactions that emerge from the multiplying number of stakeholders involved in the automotive ecosystem as a result of EM (Dammenhain & Ulmer, 2012; Kley, Lerch, & Dallinger, 2012). This new industrial ecosystem will include established industry actors, such as automotive OEMs and their networks of suppliers, as well as a range of new actors and stakeholders involved at the interface between PEV users and the electrical grid: IT providers, EM providers and technology suppliers, public sector projects and initiatives, providers of charging and battery swapping infrastructure, electrical utilities, grid

[17] California has invested more than USD $38 million into commercial, workplace, residential and fast charging infrastructure (California energy commission, 2017).
[18] An Ontario Government grant program has awarded nearly CND $20 million in public private partnerships for Level 2 and 3 EV charging stations (MTO, 2017b).

operators, and all levels of government (Dammenhain & Ulmer, 2012). In essence, social and industrial systems that were previously distinct under the existing paradigm would need to interact and, likely forge new connections and partnerships with one another (Wells, 2013). For instance, the production and use of PEVs will link the automobile industry and the personal transport sector with electrical utilities, battery producers, software and electronics producers, and metal industries in unprecedented ways.

A transition towards EM requires commensurate changes in several related areas including charging infrastructure, government taxation and incentive programs, insurance policies to accommodate new mobility concepts[19], specialized maintenance and aftercare facilities for PEVs, and other affiliated sectors and businesses (Wells, 2013). Merging these previously distinct systems together adds complexity but also presents an array of new prospects for potential partnerships, business models, and value creation for all involved. A future EM ecosystem will inexorably look quite different from the system that currently exists. There is mounting pressure on all involved stakeholders (including the public sector) to plan strategically for the future by exploiting business model innovations and novel technologies to position themselves favourably in a future characterized by new mobility trends, including EM.

7.2 Challenges Facing Automakers' Electric Vehicle Strategy

The stakes are high for those involved in EM; however, the threat to existing VMs is even higher (Hensley, Knupfer, & Pinner, 2009). A shift towards PEVs would have a significant effect on all aspects of the automotive supply chain from inbound and outbound logistics to in-house competencies, namely ICEs and transmissions (Klug, 2012). As the demand for PEVs increases, VMs will have to reinvent how they create and capture value by developing new core competencies and new business models to survive in an increasingly competitive EM ecosystem. Initially, battery manufacturers and tier-one suppliers will likely control much of the value associated with battery technologies and their related electronics, meaning VMs will have to determine how to best develop their relationship with these stakeholders over time. Most VMs have, to date, partnered with battery manufacturers to develop first generation EVs.

[19] Some Canadian insurance providers have already begun to accommodate insurance gaps created by ride hailing services offered through Uber and Lyft (CBC, 2016).

Looking ahead, VM should develop a plan to capture the value implicit in owning the software and electronic components that determine the actual performance measures of electrified powertrains, including power- and thermal-management systems. This move is critical to ensuring that the bulk of the new value implicit in PEVs is not left in the hands of their suppliers (Hensley, Knupfer, & Pinner, 2009). By gaining new competencies with respect to PEVs, OEMs can create value for performance-oriented consumers by designing a distinctive driving experience and maximizing the inherent performance advantages of electrification. Electric motors offer superior acceleration to ICE vehicles because electric power is available immediately and equally at all speeds, creating a unique driving experience. On the other hand, the energy density of currently available batteries have yet to match that of ICEVs, meaning PEVs tend to have a lower range than what customers are accustomed to. One way of enhancing the range of PEVs is by seeking weight reductions, either through lightweight materials and/or through design efficiency: tailoring vehicle designs to specific needs (e.g., urban living) rather than offering multi-purpose vehicles characterized by superfluous design elements and features (Bohnsack, 2013). The heavy all-steel body that characterizes traditional ICEVs is not only ill suited for PEVs in terms of weight, but also in terms of production flexibility.

The longer payback period associated with higher priced PEVs suggests that owners may need to extend the lifespan of their vehicle to afford the technology, which could reduce net automobile demand. This could require VMs to shift the emphasis of their business towards value captured during the use phase of vehicles rather than focusing exclusively on new vehicle sales (Wells, 2013). In the future, minimizing the lifetime "usership" costs (or TCO) for consumers will become more important than minimizing the initial purchase price given the anticipated shift towards more sustainable forms of mobility, including EM and novel mobility concepts. Strategic planning to acquire new capabilities and to create new value propositions with their business models should start now as early adopters begin to create a substantial market for electric vehicles, especially in the face of government incentives that are helping to bridge the price gap that still exists between PEVs and ICEVs.

Electric vehicles will likely have an increasingly disruptive effect on the automotive industry as their market share burgeons along with consumer demand due in part to ongoing technological improvements driving down the cost of batteries, greater availability of long range

BEVs, and larger public charging networks (Knupfer, Hensley, Hertzke, & Schaufuss, 2017). Simultaneously, automakers are facing increasingly stringent regulatory requirements at various levels of government to increase fleet-average fuel economy and increase the sale of ZEVs. Despite these multiple and compounding pressures to invest in PEVs, OEMs face four primary challenges that—if left unaddressed—could hinder their profitability when it comes to the sale of PEVs: unfavourable battery economics; the trade-off-trap between ICE optimization and PEV technology; capital competition among mobility mega-trends; and lastly, a mismatch between the supply and demand of PEVs.

7.2.1 Unfavourable Battery Economics

Despite continuing progress to reduce battery prices, which have fallen nearly 80% since 2010, unfavourable battery economics could persist—as a profitability barrier for OEMs—for the next two to three product cycles (Knupfer et al., 2017). Estimates of battery costs reveal that price parity with ICEs may not occur until sometime between 2025 and 2030. This means that OEMs may have to contend with the possibility that they will lose money on each PEV they sell until battery prices are in line with ICEs[20]. As a large incumbent OEM, GM is willing to absorb a financial loss on each Bolt EV it sells to enhance its brand image and its appeal to younger, tech savvy consumer who may not have otherwise considered a Chevrolet. In addition, GM is demonstrating that it can compete with new competitors like Tesla, which appeared to be leading the way for BEVs before the release of the Bolt—the first mass market priced long range EV (Welch & Lippert, 2016).

7.2.2 Internal Combustion Engine Optimization vs. Technological Innovation

The unfavourable prospects for the profitability of PEVs create a challenging and risky environment for VMs. On the one hand, they must comply with environmental regulations or face financial penalties, while on the other, they must make rational business decisions regarding their bottom line. This involves making trade-offs between investments in ICE optimization—which is likely to remain their primary profit driver over the short term and a core component of future HEVs and PHEVs—and R&D investment to develop future PEVs (Knupfer et al., 2017). Most global VMs have chosen to pursue incremental improvements to ICEs over investing too

[20] Reportedly, GM loses between $8,000 and $9,000 on every Bolt EV it sells while Sergio Marchionne said in 2014 that FCA lost $14,000 on each Fiat 500 BEV it sold in California to comply with regulations (Welch & Lippert, 2016)

heavily in AFVs, but Knupfer et al. (2017) estimate that a sizeable gap is likely to remain between CO_2 reductions obtained with through incremental improvements and the anticipated future regulatory requirements for CO_2 emissions. More efficient ICEVs may seem favourable at the moment but, this is unlikely to continue as each round of efficiency improvements delivers diminishing efficiency returns and costs more than the last.

7.2.3 Increasing Capital Competition from Other Mobility Mega-Trends

Electrification is not the only mega-trend constraining the capital of VMs. It is anticipated that EM will evolve alongside other major technology-driven trends: connected cars, autonomous driving features, and new mobility concepts (McKerracher et al., 2016). As these technologies develop, they are likely to become less isolated and increasingly become mutually reinforcing as they are combined and their synergies exploited through new business models. Nevertheless, at this point in their development they represent competing priorities for OEMs, further squeezing their already limited investment capital for R&D and creating a so-called "capital crunch" (Knupfer et al., 2017). Investments into PEVs must compete against ICE optimization, which has a higher short term ROI, but also, increasingly, against other nascent technological innovations. With competition for capital funding increasing on multiple fronts, the importance of determining how, when, and where to disinvest human and financial capital in ICE technology is even more critical (Knupfer et al., 2017). Moving forward, automakers must attempt to predict and understand the pace and level of impact that each of these tech-trends will have along with any potential trade-offs that will need to be made to craft an appropriate plan for the future that, ideally, maximizes any potential upsides while simultaneously minimizing any anticipated adverse effects of each technology (McKerracher et al., 2016).

7.2.4 Supply-Demand Mismatch

A significant impact and challenge related to these capital constraints at VMs is the incongruity between current consumer demands and commercially available PEVs. The number of PEVs available on the market today has grown substantially over the last few years, but there remains a mismatch between the PEVs that are available and the models, platforms, body styles, and features that are being demanded by nascent early adopters (Knupfer et al., 2017). For instance, small car-based crossovers have been experiencing double-digit growth in major automotive markets in China, North America, and Europe, but they are not yet well represented in the PEV market. This suggests that capital constrains at VMs are restricting the range of PEVs available on the market creating a barrier to increasing demand.

7.3 How Can Automakers Be Profitable in an Electrified Mobility Ecosystem?

Provided the likelihood of a future automotive ecosystem that incorporates EM to a significant degree, how can individual firms ensure that they will remain profitable given the major challenges outlined above? Analysts suggest that OEMs must combine both their internal and external capacities to ready themselves for a transition towards widespread PEV adoption, which could potentially rework how value is created and how profits are generated in the automotive ecosystem (Knupfer et al., 2017). This creates difficult circumstances for automakers who will have limited maneuverability as they explore new strategies while increasingly relying on trial and error to determine which one is most effective. Automotive OEMs will have to strengthen their understanding of the diverse preferences held by potential PEV consumers and determine how this knowledge can be used to inform the development of a corporate EM strategy. For instance, surveys conducted in the US and in Germany have noted a gap between the perceived charging requirements and range anxiety of potential PEV consumers versus the actual driving experience of PEV owners. Partly contributing to this are the misconceptions potential consumers often have about the technology and the lack of information regarding lifetime costs or TCO, reliability, and driving experience among others. Appropriate marketing and consumer education will be necessary to dispel misconceptions and shift the focus towards the considerably lower lifetime maintenance costs of PEVs and their enhanced performance and driving experience thanks to instantaneous torque, factors often deemed important by early adopters (Knupfer et al., 2017).

Along with a deep understanding of consumer preferences, traditional VMs should harness their inherent advantage over new entrants. Tesla has been successful in generating crucial consumer enthusiasm and media buzz around its products and its brand to ensure consumers are willing to pay a premium for its technology and the Tesla badge. However, survey results by Knupfer et al. (2017) show that consumers place the highest levels of trust in traditional brands with a much longer legacy in the industry. According to the authors, these results suggest that a potentially fruitful strategy for established automakers to leverage their brands and their history, while also generating Tesla-esque excitement, could be to introduce a sub-brand that focuses exclusively on electrified vehicles—in similar fashion to what BMW has done with its "*i*" branded PEVs, the i3 and i8. Sub-branding has long been used in the industry to emphasize higher performance variants such as Mercedes-AMG, BMW M, and Audi RS. Perhaps the same sort of strategy could be useful to encourage greater excitement and desirability around PEVs. Existing global OEMs will have to learn how to use their vast knowledge and existing brand power to maintain market share in the face of intensifying competition as technology companies and new entrants venture into the automotive ecosystem fueled by the aforementioned technology driven trends that are evolving alongside EM.

Automotive OEMs must also attempt to understand and identify differences in the preferences of existing versus emerging consumer segments. Depending on their stage of adoption, current early adopters will likely have different preferences than adopters in later stages. The varying needs and expectations of the different consumer "horizons" should not be overlooked. Knupfer et al. (2017) suggested that there is currently a market for more basic EM solutions that do not require an ICE equivalent electric range. Specifically, consumers familiar with PEVs may have distinct expectations that are more in line with current technologies and that are different from those of consumers in later stages of adoption who are less willing to make compromises or to pay for innovative technologies. Understanding the differences between various consumer horizons could be crucial to framing marketing campaigns and packaging vehicle features appropriately to attract both existing and emerging consumer segments as part of an EM strategy that evolves alongside the market.

When it comes to meeting the needs of mass market consumers who are likely to have higher expectations for PEVs in terms of range, performance, and vehicles features but who are similarly unwilling to pay a premium for such preferences, VMs will likely have to explore new strategies—or potentially, entirely new business models—in order to meet the needs of these consumers while remaining profitable. This will likely require OEMs to move away from their current model of selling mobility products (i.e., simply selling new vehicles) to selling MaaS, or as an integrated package of products and services (Knupfer et al., 2017). Embracing new mobility concepts in their business models will be essential if traditional VMs are to remain profitable and competitive; one possibility is to shift the economics of PEV ownership away from the initial costs or purchase price to lifetime costs or TCO. Successful strategies will leverage the unique capabilities of PEVs in order to satisfy consumer demands in an entirely new way while also providing automakers with a mechanism of offering consumers more capable PEVs at higher price points by focusing on TCO and selling mobility rather than car ownership through user fees, subscriptions, or comprehensive lease agreements (Knupfer et al., 2017). If implemented promptly and properly, this could provide a first mover advantage and potentially a larger share of the nascent long-range PEV market.

7.4 New Business Models for Electric Mobility

The business model concept is taking on a notable role in both academic and business literature with regards to EM and sustainable eco-innovation in the automotive industry. The primary motivation for developing a new business model or re-structuring a pre-existing model is to increase consumer benefits by satisfying their perceived needs with innovative solutions and approaches (Kley et al., 2011). Innovative business models can also be useful in securing a competitive advantage against rival firms and, to a degree, bypassing traditional incumbents by finding new ways of creating and capturing value (Andersen et al., 2009). There is growing intrigue into the business model concept with respect to EM as it could be a useful mechanism for VMs to offset the higher cost of PEVs and improve consumer acceptance through the provision of additional services and creating new and unique value opportunities. Christensen et al. (2012) pointed out that business model evolution is primarily triggered by some sort of technological innovation, either in the product/service or in the underlying business process, or by economic distress within the existing business model that reduces its competitive power. Christensen et al. (2012) agreed that business model innovations often “emerge in turbulent technological, economic and regulatory context, when new ways of conducting business become possible” (p. 499) or in the case of the automotive industry when new ways of conducting business become necessary with regards to continued economic and environmental sustainability.

The global automotive industry, arguably, satisfies all of these pre-conditions. Electrification represents a radical technological change while the industry itself can be characterized by repeated periods of economic distress with some global automakers having reported prolonged periods of financial losses in major traditional automotive markets. California’s ARB was also a leader in implementing radical environmental regulations requiring automakers to invest in ZEV technologies. Given this context, automotive stakeholders should be exploring alternative business models in an effort to establish a competitive advantage in light of new competitors and new industry dynamics. Furthermore, business model innovation is often considered a prerequisite for the widespread acceptance and adoption of PEVs and, therefore, the broader sustainability benefits of the technology (Christensen et al., 2012; Beaume & Midler, 2009). Electric mobility not only represents an opportunity to explore new business models, but EM itself requires new business models in order to become competitive in mainstream markets against existing technologies.

A business model "describes the design or architecture of the value creation, delivery, and capture mechanisms" explicitly or implicitly employed by a business enterprise, or more simply it defines "the manner by which the enterprise delivers value to consumers, entices consumers to pay for value, and converts those payments to profit" (Teece, 2010, p.172). Based on this definition, a generic business model can be divided into three primary elements: (a) the value proposition; (b) the configuration of the value chain; and (C) the revenue model (Kley, Lerch, & Dallinger, 2011). Kley et al., (2011) argued that a shift within each of these elements is inevitable in the context of EM because the industry's classical business model—in large part designed around the ICE—cannot simply be adapted to accommodate an innovation like EM due to inherent technological restrictions.

Often considered a disruptive force in the automotive industry, Tesla's business model remains highly product-focused and shares many elements with the classical automotive business model, including a traditional revenue model based on individual ownership. Furthermore, Tesla's ambition to ramp up its production volumes to compete with industry incumbents reflects its desire to manufacture BEVs within the industry's existing production and consumption paradigm. Tesla's innovative value proposition stems instead from its novel direct sale retail concept, which includes an online ordering process and the ability of some owners to access a proprietary fast charging, inter-city supercharging network free of charge to facilitate long distance travel. This unique value proposition was intended to reduce range anxiety and allow Tesla owners to make long distance trips, previously only suitable for an ICEV. The configuration of Tesla's value chain is somewhat different as it integrates new stakeholders at the interface between the vehicle and the electrical grid and a new network of "refueling" infrastructure. However, Tesla's revenue model is essentially unchanged in terms of how consumers are able to pay for this value either at the point of sale or by entering into a traditional finance or lease agreement.

A variety of new business models could arise as a result of the interactions within a new network of stakeholders involved with EM as they sort out how to define, or re-define, their share of the value chain. Self-contained business models will no longer be able to operate in isolation given their interaction with new stakeholders and the potential for new value opportunities resulting from EM (Wells, 2013). Electrification will inevitably challenge traditional VMs, as the necessary changes for the success of PEVs are likely to undermine their existing business model, which is based primarily on the production, distribution, and marketing of finished steel-bodied ICEVs. Incumbents tend to resist changes that conflict with their existing business practices, procedures, and operational norms (Christensen et al., 2012). This means new entrants, who are more willing to consider new and innovative business models, might have an advantage over their more established competitors (Bohnsack, 2013). There is some level of risk and uncertainty involved with pursuing a new business model as it remains unclear at this point, which strategy—or combination of strategies—will prove to be the most effective or have the greatest revenue stream. There is also, however, risk in maintaining the status quo. There is mounting pressure on all stakeholders to develop new business models, as consumer increasingly demand new value propositions and as first movers begin to enter and disrupt the market with innovative solutions to satisfy consumers' mobility demands (Kley et al., 2011).

The successful commercialization of PEVs will require accompanying business models that can overcome the myriad socio-technical barriers that have, to date, dampened their demand (Bohnsack, 2013). By itself, a technological innovation—no matter how superior—does not guarantee commercial success. Superior technologies often fail because of the ill-conceived business model used to introduce them to the market; a well-defined business model is one that establishes a target market and a strategy for capturing value from that market (Teece, 2010). An innovative product that is new to consumers requires a tailored business model that effectively enhances market acceptance and, ideally, provides a competitive advantage that is distinguishable and not easily emulated by the competition. Wells (2013) contemplated in his commentary on sustainable business models for the automotive industry the degree to which the lack of uptake of PEVs is due to the technology itself or to the lack of penetration of innovative business models by either established brands or new players in the industry.

A case study of the implementation of BEVs by EM company *Better Place* in Denmark revealed that even an innovative business model paired with a new technology can be insufficient against the barriers to change embedded in established business practices (Christensen et al., 2012). The authors contended that the Better Place example illustrates that business models should not simply be about how enterprises create and capture value, but should be about how related firms and agencies can benefit by examining internal and external relations of the business. For instance, the long-term success of the Better Place business model should have included an evaluation of the number of PEVs that could be supported by the existing electrical grid before having to increase its capacity insofar as it relates to PEV charging.

Despite the importance of business model innovation in supporting a transition to EM, implementation is not a straightforward task. Established businesses face significant barriers when it comes to developing and experimenting with new business models. Business managers are less likely to embrace experimentation with business models that threaten the value of the enterprise's existing assets. Incumbent firms often resist disruptive innovations because of "the conflict between the business model already established for the existing technology, and that which may be required to exploit the emerging, disruptive technology" (Chesbrough, 2010, p. 358). What often ends up happening, and a current challenge for global automotive OEMs, is the established technologies are disproportionately favoured when it comes to the allocation of capital and other resources. Significant barriers to market acceptance and diffusion of disruptive technologies will always mean that innovative products will have, at least initially, lower profit margins than the established technology, a further disincentive for firms to experiment with new business models for these technologies.

7.5 Business Model Evolution: Incumbents vs. New Entrants

Bohnsack, Pinkse, and Kolk (2014) conducted a qualitative analysis of PEV initiatives by key industry players to determine the respective impact of path-dependent behaviour on the approach, used by incumbent and entrepreneurial firms (new entrants), to business model innovation by tracking changes to their value proposition, value network, and revenue/cost model over time (2006 – 2010). The analysis identified four business model archetypes: Luxury specific-purpose (i.e. Tesla Roadster); luxury multi-purpose (i.e., Fisker Karma); Economy specific-purpose (i.e., Th!nk EVs and Daimler's car2go with the Smart ForTwo electric-drive); and economy multi-purpose (i.e., Chevy Volt, Nissan Leaf, Mitsubishi iMEV, Better Place).

The results generally indicated that the various business model archetypes distinguished in the analysis required different configurations of integrated products and services to overcome the primary technological barriers associated with PEVs: higher purchase price, limited driving range, and uncertainty about battery lifespans (Bohnsack et al., 2014). The integration of a service component to compensate for these barriers was more important for EV initiatives targeting the more price sensitive economy segment. Initiatives targeting the less price sensitive luxury segment were not only less concerned with the higher cost of PEVs but also on the provision of services to compensate for the need for frequent recharging. A common feature among all four business model archetypes was the level of evolution and change that occurred throughout the five year study period (Bohnsack et al., 2014). Of particular interest to the researchers was the degree to which path-dependence influenced business model evolution within each archetypes and if there were observable differences in the approach used by incumbent and entrepreneurial firms.

In accordance with the existing business model literature, Bohnsack et al. (2014) found that in the case of the car industry, incumbent car firms approached their PEV business models differently than did entrepreneurial car firms. The former were focused mainly on efficiency for value creation, with the goal of mass production from the outset, while the latter were the main source of novelty and business model innovation that later diffused throughout the industry. Incumbent firm were found to be the most influenced by path-dependence, constraining their behaviour to incremental innovations that were more or less in line with their existing business logic, targeting the same consumer groups with a product focused business model. With respect to business model evolution by incumbents, most of the adjustments were made to the cost/revenue model to save on costs and lower the purchase price of their PEVs. Incumbents also made adjustments to other business model components including the provision of additional services (i.e., leasing batteries independently, providing extended battery warranties, and providing access to an ICEV for longer trips), and outsourcing core EV components from external suppliers with the proper expertise. It should be acknowledged, however, that most of these tactics had been previously applied in the industry to conventional ICEVs and were therefore not entirely unfamiliar. A few notable exceptions of incumbents straying further from their traditional product focused business model was Daimler's car sharing initiative car2go, which made use of its Smart brand's novel design and alternative retail and product strategy for experimentation, and BMW's *i* sub-brand or purpose built PEVs (Bohnsack et al., 2014).

Entrepreneurial firms on the other hand were able to introduce key novelties in their business models to overcome inherent drawbacks associated with PEVs that later diffused throughout the industry. Before evolving into more novel business models, these firms initially found innovative ways to create value for consumers. Fisker and Tesla emphasized performance and luxury within a consumer segment that was willing to pay these premium features, including superb acceleration. In the economy segment, Better Place attempted to tackle the hassles associated with having a limited range and having to frequently recharging the car's battery by introducing a novel payment system through a mobile smartphone application. Despite their initial attempt to introduce novel business model strategies, contingent events that were both external and internal to the automotive industry led to greater convergence between incumbent and entrepreneurial firms, which were now pursuing less expensive PEVs that could be produced at higher volumes. Thanks to the success and subsequent "halo effect" of the Tesla roadster, Tesla gained a greater sense of legitimacy in the eyes of consumers and was the only entrepreneurial firm to sustain its activities beyond the five year study period that ended in 2010 (Bohnsack et al., 2014). This demonstrates the higher susceptibility of entrepreneurial firms in the face of contingencies such as the 2008 financial crisis.

The global financial crisis was a major external catalyst that resulted in widespread impacts to the automotive industry. The financial bailouts of GM and Chrysler were contingent upon certain sustainability requirements, which helped sustain EV development. Furthermore, the US government launched the Advanced Technology Vehicle Manufacturing direct loan program, which allowed VMs to apply for loans to develop PEVs and other green technologies (Bohnsack et al., 2014). However, the program's short timeframe favoured incumbent firms and existing entrepreneurial firms that also had access to existing assets to benefit from these incentives. Incumbents with larger internal revenue streams to finance new projects were able to move much faster in response to these incentives and bring PEVs to market much sooner.

Incumbents were able to leverage existing hybrid models and develop them into plug-in versions with fairly minor technological changes. Both GM and Nissan developed purpose-built PEVs, with the Volt and Leaf respectively, by using existing vehicle platforms. It was also thought that over time, incumbents' dealer networks would move towards being a significant asset as they become involved in delivering new service-based components as part of their value proposition. A new entrepreneurial firm without existing complementary assets generally needs much more time to bring a vehicle to market. The government loans also led to greater convergence in the economy multi-purpose segment as entrepreneurial firms that had already entered the market were able to use them to broaden their business model. The halo effect initially created around Tesla's initial success later extended into the rest of the EV market. Automakers began investing in their own internal capabilities under the growing assumption that battery technology would become key to future competitiveness in the PEV market. Initially however, it was the lack of control that incumbents had over batteries' technological progress as a result of outsourcing that subsequently led to the key business model innovations (e.g., substitution with and ICEV, battery swapping, and car sharing) that eventually diffused throughout the automotive industry (Bohnsack et al., 2014).

Incumbent firms were generally more resilient to changes resulting from contingent events given their existing complementary assets and internal capital; whereas incumbent firms dealt with greater uncertainty given that much of their funding was dependent on government grants and venture capital. This uncertainty and greater susceptibility is evident in the fact that Tesla is the only remaining entrepreneurial firm that was studied. Path-dependent behaviour was observed at incumbent firms with their dominant business model logic, complementary assets, and contingent events creating a self-reinforcing mechanism that kept them near to their existing practices. Although it was expected that entrepreneurial firms would focus on a primary business model, making marginal adjustments over time by adopting knowledge from adjacent industries, incumbent firms essentially did the same by focusing on a single business model as opposed to experimenting with several different initiatives simultaneously. Most of the business model changes made by the observed firms were small adjustments relating to the value network and the revenue/cost model as opposed to more radical adjustments to the core value proposition. The authors also concluded that since the study period occurred relatively early in the development of the EV market, business model changes would become less pronounced over time as the industry approached a more stable state. Lastly, although many of the key business model novelties were initiated by entrepreneurial firms, the authors noted that incumbents were actively developing their EV business model and therefore, felt that labelling them as followers would have been inappropriate (Bohnsack et al., 2014).

7.6 Business Model Innovation through Product-Service Systems

Similar to the novelties and business model innovations initially pursued by entrepreneurial firms, the notion that new and innovative business models are necessary to overcome barriers to PEVs and increase their acceptance and adoption among potential consumers is gaining more recognition. A successful business model innovation should structure the value proposition in such a way that lowers TCO while offering additional value added benefits to consumers (Kley et al., 2011). With respect to PEVs, business model innovation could be used to spread out their higher cost over the vehicle's lifetime by emphasizing TCO, while ensuring VMs can remain profitable. Automakers should leverage current technology-driven mobility trends as part of sustainable business model innovations to solidify their role in future automotive value chains and to maximize their profitability potential while improving consumer satisfaction.

The concept of integrating products and services into a Product-Service Systems (PSS) has become an increasingly relevant topic in the business and sustainability literature. Tukker and Tischner (2006) defined PSS as "a mix of tangible products and intangible services designed and combined so that they are jointly capable of fulfilling final consumer needs". Mont (2002) suggested that the focus of a PSS should be on creating system-based solutions that facilitate a shift away from the dichotomy that exists between systems of production and consumption. When defining PSS, the author included the integration of supporting networks and infrastructure, along with products and services, and suggested that to ensure its competitiveness a PSS should be designed to satisfy consumers' needs and reduce environmental impacts to the system. This broader definition of PSS is relevant to EM because it requires new stakeholders and networks of interactions between them, and new infrastructure with which consumers must use and interact with in new ways.

The integration of products and services in a PSS to jointly fulfill users' needs encompasses a range of strategies concerned with "the management of products throughout their life cycle in an effort to minimize environmental impacts and to identify alternative profitable revenue streams" (Williams, 2006, p. 176). New notions of ownership, new product designs and services, and new forms of producer-consumer interactions have all formed part of existing business-to-business or business-to-consumer interactions but have yet been unified into a coherent whole to form a "full" PSS (Williams, 2006).

Generally, OEMs have very few direct interactions with consumers; those relationships are forged and maintained by franchised dealerships on their behalf. In a PSS, VMs control the consumer interface and retain ownership of their products, fundamentally changing how producers interact with their products and their consumers. By retaining ownership of their products, producers would endeavour to limit lifetime costs by extending product lifespans and improving durability. Manufacturers would also be responsible for taking back ELVs, encouraging product designs for easy recyclability and upgradability, and bringing circularity to their supply chains. The benefits of AM could be leveraged by PSS to extend product lifespans; 3D printed component modules could be designed to promote easy removal for replacement, upgrading, or recycling.

The relationship between producers and consumers would also be affected by PSS, which "entails not only a product, but also the services that surround it, and the information that a consumer and firm impart on each other" (William, 2006, p.177). New forms of interaction and information sharing could lead to the creation of formal feedback loops between manufacturers, which could provide information on how to minimize the environmental impacts of their products, while consumers could impart valuable product information relevant to manufacturers for design purposes or to improve efficiency. Williams (2006) regards PSS as a practical approach towards innovation at a functional and systemic level as opposed to focusing exclusively on environmental innovations at the product level.

Vezzoli and Ceschin (2008) posit that the eco-efficiency benefits of sustainable business model innovation through PSS is derived from the novel stakeholder iterations and shared economic interest that emerge when a variety of different socio-economic stockholders are brought together to create a "satisfaction system". The convergence of economic interest between stakeholders in a particular value chain or "value constellation" through innovation at the product level and critically, at the level of inter-firm cooperation (including new forms of interaction and partnerships) provides an incentive for firms to reduce their resource use. The reason being is that individual stakeholders are generally involved with a single life cycle phase. This promotes apathy among individual firms to improve the overall eco-efficiency of product life cycles insofar as it does not affect the economics of their business model. Thus, there is no incentive for firms to improve system eco-efficiency and might even be encouraged to reduce product longevity to accelerate turnover. As such, innovative stakeholder interactions that either (a) extend a stakeholder's involvement into multiple life cycle phases of different products and services within a PSS; or (b) extends the length of time a particular stakeholder interacts with a given product life cycle or PSS, can create an environment where the eco-efficiency of the systems converges with the economic interest of individual firms (Vezzoli & Ceschin, 2008).

By designing business models as "need-fulfillment systems" in which the focus is placed on the needs of consumers and the provision of desirable services, rather than on final products, a PSS has the potential to dramatically reduce environmental impacts (Tukker, 2015). Shifting a firm's focus away from the design and sale of tangible products (i.e., product oriented business models) to the provision of a mix of services involving the use of a product (i.e., service-oriented business model or PSS) to satisfy a particular need or demand fundamentally changes their economic interests. While the former incentivizes higher volume and sales through market expansion and faster product turnover to generate profits, the latter turns products into cost centers rather than profit generators, which incentivizes firms to prolong product lifetimes, increase use-intensity, and minimize product costs and material intensity (Tukker, 2015). This is possible because in a PSS, profits are generated through the provision of product-related services which helps align a firm's economic interests with improved product longevity and sustainability.

In the current automotive paradigm, increasing production volumes drives economies of scale, which are necessary to cut costs and improve profit margins, thereby amortizing production costs over the greatest number of units (Vezzoli & Ceschin, 2008). The high capital costs of automotive production related to conventional product and process technologies create high breakeven points that necessitate mass production. This severely restricts the flexibility of VMs and the number of alternative available to them. The industry's conventional logic encourages turnover and technological obsolescence, resulting in high resource intensity and waste generation. Conversely, a PSS based on EM could increase eco-efficiencies and minimize material flows by converting linear flows into circular ones while potentially improving consumer satisfaction.

7.6.1 Types of Product-service Systems

The literature generally distinguishes between three primary types of PSS: product-oriented services (e.g., maintenance contracts or extended warranties, financing schemes, ELV take-back programs, providing vehicle efficiency information, and providing traffic avoidance information/services); use-oriented services (e.g., vehicle leasing, car sharing, carpooling); and result-based services (e.g., pay per service unit and functional result). Williams (2007) conducted a systematic review of both existing and planned PSS initiatives in the automotive industry to assess their contribution to system-wide innovation along five evaluative criteria[21]. The results indicated that at present only the "functional result" type of PSS has the capacity to provide the diversity of changes necessary to enable system innovation (Williams, 2007). By focusing on the provision of an end-result without specifying how it is delivered to the user, mobility providers are given the flexibility to illustrate the specified outcome through a variety of means to maximize both efficiency and sustainability. For instance, a functional result could be delivered through an integrated, multi-modal mobility scheme that includes public and/or active transit, and mobility services like car sharing or ride hailing.

The authors noted that most of the reviewed PSS initiatives did not recognize the importance of providing a total or complete offering to satisfy mobility requirements, which is necessary to maximize the benefits of a full PSS. The researchers acknowledged that many of the initiatives were focused on showing off new technology as opposed to truly "exploring and exploiting how new technological opportunities can offer new ways of providing mobility and sustainability" (Hoogma, Kemp, Schot, & Truffer, 2002, p. 5, as cited in Willams, 2007). This suggests that there is untapped potential within current and planned PSS in the automotive industry. For this reason, this paper has chosen to present the PSS in the context of AM and EM, two radical—and potentially disruptive—technologies that in the opinion of this thesis should be

[21] "Evidence of 'higher-order' learning amongst stakeholders; changes in infrastructure and institutional practice; changes in vehicle design, manufacture and end-of-life management; changes in vehicle ownership structure; changes in modes of producer-user interactions." (p.1093)

leveraged in the transition towards sustainability in the automotive ecosystem as proposed by the theoretical MFR concept.

7.7 Micro-Factory Retailing: A Platform for Integrated Product Service Systems

As described in more detail by Williams (2007), the MFR concept could be an ideal mechanism for delivering full PSS in the automotive industry to drastically improve sustainability and address the limitations of current and planned PSS in the automotive industry. The small scale and local nature of the MFR concept means that there would be an opportunity for locally sourcing certain parts and materials. In addition, logistics networks associated with more generic component modules and sub-assemblies manufactured in centralized facilities would likely be more economically and environmentally efficient than existing logistics networks tasked with transporting and delivering fully assembled vehicles across long distances. Another major benefit of the MFR concept is the design freedom that becomes possible without the constraints of the all-steel body (Wells & Orsato, 2004). The separation of car bodies from car frames and chassis means increased opportunities for modular design concepts, which can be further enhanced using AM—as suggested by this thesis. This type of vehicle architecture also presents novel opportunities to introduce alternative powertrains, including electric propulsion systems, while overcoming some of the barriers associated with these alternatives. Theoretically, the same car body and interior could be placed on a chassis with either an ICE or an electric powertrain, and could be easily switched if necessary (Williams, 2007). The integration of vehicle manufacturing and retail sales in the MFR concept and its proximity to consumer markets means that these sites could “facilitate the type of enhanced producer-consumer interactions envisaged as part of a PSS” by allowing for the direct interaction and information exchange between staff involved with vehicle design and manufacturing, and consumers (Williams, 2007, p. 180). Furthermore, MFR sites are ideally suited to provide repair and module upgrading and replacement services as well as managing the take back, recycling, and potential refurbishment of ELVs. The take away here is that fundamental principles of MFR align well with those in PSS and could therefore provide an ideal interface for the provision of more radical and fully integrated PSS, further enhancing the economic and environmental sustainability of the automotive industry—especially when integrated with EM and AM.

Similarly, Vezzoli and Ceschin (2008) hypothesized an "alternative business model for a sustainable satisfaction system" (p. 6) in the automotive industry and noted that "the MFR approach can potentially facilitate the adoption of eco-efficient PSS via aspects such as the unification of the commerce and manufacturing functions, and the proximity of manufacturing and servicing sites to users". The researchers proposed further enhancements to maximize the benefits of MFR by suggesting that small, local manufacturers should operate not in isolation but in cooperation with energy and insurance providers to facilitate the provision of mobility while ensuring product ownership remains with the VMs. Furthermore, a PSS facilitated by such partnerships and MFR sites could collaborate with local authorities and local public transport providers so that mobility could be delivered as a "unit of satisfaction" and paid for on the basis of distance covered, including the use of a vehicle, energy requirements for charging, insurance and maintenance requirements, as well as access to parking and public charging infrastructure. Several key innovative characteristics emerge from an alternative model that, like this thesis, envisions the provision of eco-efficient PSS through MFR sites.

First, innovative stakeholder interactions are necessary to engage all stakeholders in the resource optimization of the entire system. Traditional life cycle phases can fragment stakeholders and breed indifference towards system issues such as resource efficiency. Second, traditional sales models would have to shift their focus from selling products to selling results. Consumers would no longer pay for individual components, such as a vehicle, fuel, and insurance, but rather they would pay for units of satisfaction through services that provide access to mobility. Third, without a product-centric focus, the responsibilities of product ownership must also shift, remaining with PSS providers or manufacturers rather than with consumers. Finally, given new structures of ownership, product designs must be altered to ensure the profitability of PSS providers. Vehicles should be designed with efficiency and dematerialization in mind and be easily upgraded, maintained, dissembled, reused, and recycled to reduce lifetime costs. As this thesis has attempted to argue, the benefits of both EM and AM should be leveraged to achieve these sustainability goals and facilitate both the use of MFR and the provision of PSS.

7.8 Accommodating Competing Mobility Mega-Trends

Electric mobility is not the only technology-driven trend with a huge disruptive potential in the automotive industry. Connectivity and autonomy are emerging alongside EM, demanding their own R&D investments and experimentation. Fortunately, much of the discussion so far on business model innovation and integrated PSS with respect to EM is equally applicable and, arguably, necessary for the development of these competing technological innovations. These mega-trends are all converging on the automotive industry simultaneously, creating unprecedented challenges for incumbents in the industry. The common thread among all three of these trends is the need for business model innovation. The industry is grappling with a shift from traditional products-oriented approaches to service-oriented approaches (i.e., MaaS) to satisfy increasingly diverse consumer needs and demands for customized and on-demand products and services.

Silberg, Mayor, Dubner, Anderson, & Shin (2015) warned incumbent OEMs of the impeding "clockspeed dilemma" that nascent consumer expectations are creating by requiring innovation to occur simultaneously at multiple scales and speeds. The convergence of large technology companies like Apple and Google, and high-tech entrepreneurial firms like Tesla Motors is exacerbating the clockspeed dilemma as innovation in these sectors often occurs much faster than traditional vehicle life cycles. To combat the onslaught of new competitors, traditional automotive manufacturers must operate simultaneously in two different worlds and at two different speeds. Current examples of fast-paced technological innovations in the automotive industry are vehicle connectivity and autonomous driving features. The development cycles of information technology hardware and software are typically much faster than traditional innovation cycles in the automotive sector, meaning traditional VMs will have to find a way to keep pace with these digital innovations or risk losing out to new competitors form Silicon Valley (KPMG Int., 2015).

Consultancy firm KPMG suggested that traditional VMs are at an important crossroads in terms of outlining their future role in a mobility ecosystem in which cars are ubiquitously connected and capable of generating large amounts of data about consumers and their behaviours (KPMG Int., 2015). To a greater extent than ever before, consumers are considering the overall package of services that are being offered to them to influence their purchasing and usage decisions. In addition to shifting consumer expectations, there is the threat of new competitors from the technology sector that are working hard to apply the knowledge they have gathered about their consumers to new revenue streams in the automotive sector. Traditional VMs must entice consumers with their own suite of product features, software solutions, and mobility services or risk being excluded from valuable new revenue streams made possible with the consumer data generated by connected cars. Analysts at KPMG International (2015) suggest that automakers must choose to either compete or not compete against innovative technology companies for data at the consumer interface, which will determine if—moving forward—they remain “metalsmiths” (i.e., keeping their business model static and acting as suppliers of finished vehicles), or “grid masters” (i.e., shifting their business model towards integrated PSS by “creating customized vehicle-independent product features and services, throughout the customer’s entire lifecycle” [p. 3]).

In the same way that automotive manufacturers will have to vigorously defend the consumer interface against new EM stakeholders, increasing vehicle connectivity will require OEMs to forge new direct consumer relationships to defend against the influx of third party firms who will attempt to step in between them and their consumers (KPMG Int., 2015). A grid master must be consumer- and service-oriented while a metalsmith will remain product- and hardware-driven. Factors that previously determined most purchasing decisions will be replaced by new criteria as consumers look to optimize their time, cost, and quality of life simultaneously. Future business models will have to reflect the needs of their consumers and be able to satisfy them in real-time using new features and applications. The data generating power of ubiquitously connected cars is immense. Automakers must integrate the use of this behavioural data into their business model innovation to create revenue streams that will remain profitable over time. As consumers and competitors become increasingly aware of the value of their data, competition for this information will increase as third parties attempt to acquire control over it and provide innovative, data-driven services. Unfortunately, this could mean that only premium brands will be equipped to maximize the potential of this data while mass-market brands will be confronted with new partnerships or arrangements with technology and communications firms. Lastly, the key to becoming a grid master and adapting quickly to changing consumer demands is the decoupling of R&D activities for vehicle-dependent and vehicle-independent hardware and software to ensure automakers can effectively operate at two different speeds of innovation and avoid the clockspeed dilemma (KPMG Int., 2015).

A recent example of a new entrant taking advantage of the increasing vehicle connectivity is Tesla Motors. The company implemented a fix to some of its vehicles in response to a recall by the National Highway Traffic Safety Administration (NHTSA) in the US for potential fire risks while charging using an over-the-air software update (Brisbourne, n.d.). This meant that none of Tesla's customers had to take their vehicles into a dealer for repair, essentially redefining what an automotive recall of the future might entail. Similarly, Tesla has issued multiple over-the-air cloud-based software updates to its autopilot driving feature, also in response to an investigation by the NHTSA (Burke, 2017).

Similar to the connected car, once the technology and capability for fully autonomous cars is established they will create many new opportunities for innovative business models and opportunities for new competitors, including major ride-hailing services like Uber who has been investing heavily in developing and testing self-driving cars in order to expand its revenue model (McKerracher et al., 2016).

Autonomous vehicles are likely to give rise to new operating models and ownership structures, further emphasizing the need for VMs to expand their revenue streams by taking full advantage of these technological trends and integrating them into innovative and integrated PSS. It is anticipated that new operating models made possible with self-driving cars will result in much greater usage intensity and possibly increase annual vehicle kilometers travelled. Therefore, self-driving cars are likely to be electric as to not contribute to an increase in GHG emissions. These vehicles should be used as part of an integrated PSS that includes charging infrastructure and public transportation to further increase sustainability and mitigate the "last mile" problem often associated with shared transportation modes like busses and commuter trains.

Chapter 8 Looking Ahead with 3D Printed Battery Electric Vehicles

8.1 Case Study Selection Criteria

This chapter will outline three innovative vehicle concepts by entrepreneurial firms, each hoping to disrupt the status quo by doing away with conventional logic and revolutionizing how cars are designed, built, and sold to improve economic and environmental outcomes in the automotive industry. The purpose of these detailed case studies is twofold: firstly, to illustrate that facets of the MFR model that are being actively pursued by innovative new entrants, validating the potential real-world applicability of MFR as a viable and achievable alternative; and secondly, to demonstrate the capacity of AM and EM to jointly enable a transition to a more sustainable production and consumption paradigm based on the MFR model.

The selection criteria used to determine the inclusion of each case study were straightforward. As denoted by the above objectives, each case had to exhibit distinct parallels with the overall objectives advocated by the MFR model. Since MFR fundamentally requires an alternative production process and product technology to be viable, eligible cases had to employ AM methods to some extent within their final production process and had to either make use of an electric powertrain or be compatible with alternative powertrain technologies, including electrification. Moreover, firms had to demonstrate some level of business model innovation rooted in sustainability. Despite utilizing novel product technologies such as electrification, semi-autonomous driving features, a lightweight aluminum body, and offering unique value propositions that include online and direct retail sales, Tesla Motors was not an eligible case because its fundamental production process is based on existing mass production methods in centralized assembly plants. Seeing as the focus of this thesis is the Canadian market, North American based companies were prioritized. Although none of the vehicle concepts are yet in production (as of December 2017), it was required that each company have had exhibited a full-sized and fully functional prototype as opposed to just a physical model. This was important to demonstrate the viability of the chosen design and its innovative production process. Finally, new entrants to the automotive industry were prioritized over established global automakers that tend to be constrained by their existing business practices and less willing or able to pursue disruptive innovations as a result.

The selected case studies were the Urbee by KOR Ecologic (Winnipeg, MB, Canada), the Strati by Local Motors (Phoenix, AZ, USA), and the Blade by Divergent 3D (Los Angeles, CA, USA). Each case study reveals the overall mission of each firm and describes the technological specifications underpinning their novel concept vehicle. It is important to note that the featured companies are not only new to the automotive industry but are actively trying to disrupt it, as such their business models and products are dynamic and susceptible to change as they evolve and determine how they can be successful and profitable over the long-term. Therefore, the descriptions contained herein depict the strategies being pursued by each firm at the time the information was collected and should be considered as only a snapshot in time within their ongoing evolution to disrupt the industry and break into the mainstream market. The chapter concludes with a discussion of the benefits of the strategies being pursued by these new entrants and the potential difficulties or barriers that may infringe on the development of 3D printed EVs in the future.

8.2 The Urbee by KOR Ecologic

8.2.1 Designing the Greenest Car Ever Built

The engineering firm KOR Ecologic, named after its president and senior designer Jim Kor, developed the world's first vehicle to feature a 3D printed exterior shell: The lightweight, jellybean-shaped, two-passenger HEV was code-named Urbee (Stratasys, 2013). The inspiration behind the Urbee car project was an electric-powered, rapid personal transit, rail vehicle—dubbed the Podcar—designed, built, and tested by KOR Ecologic's team of designers and engineers (Bargmann, 2013). The team's aspirations for the Urbee were similar to that of the Podcar: to revolutionize the future of sustainable personal mobility. The difference was that Urbee would rely on the vast network of existing roadways as opposed to requiring a new network of infrastructure. The engineering team began working towards a prototype vehicle in 1996, and gradually refined their design over the subsequent decade.

Collectively concerned about climate change and the irreparable damage that was being caused by the combustion of fossil fuels, KOR Ecologic set out to innovate a solution to mitigate the effects of GHG emissions on future generations and to be a catalyst for change in the personal mobility sector (Kor, 2012c). Urbee's design was based on a scientific approach with "an unwavering emphasis on energy efficiency" and was intended to represent an alternative to the fundamental design of contemporary automobiles (Kor, 2012c). The result was a lightweight (<600 kg), low-energy, and highly aerodynamic HEV with ethanol as backup designed for urban use and powered by renewable energy—Urbee’s name was derived from the words urban, electric, and ethanol (Bargmann, 2013). The Urbee’s rather unorthodox, truncated teardrop shape is incredibly aerodynamic and was chosen—despite some opposition—to maximize its efficiency, which Kor insisted was to be prioritized over the vehicle’s aesthetics. The streamlined body was refined using simulation software (Figure 2) to minimize the vehicle’s coefficient of drag (Cd), a dimensionless measure of the resistance created by an object in a fluid environment. The Urbee had the lowest Cd of any multi-passenger vehicle, at 0.149, a value that is substantially lower than Toyota’s newest version of the Prius hybrid, which features a Cd among the lowest of any current production vehicle at 0.24 (Bargmann, 2013; Toyota, 2017).

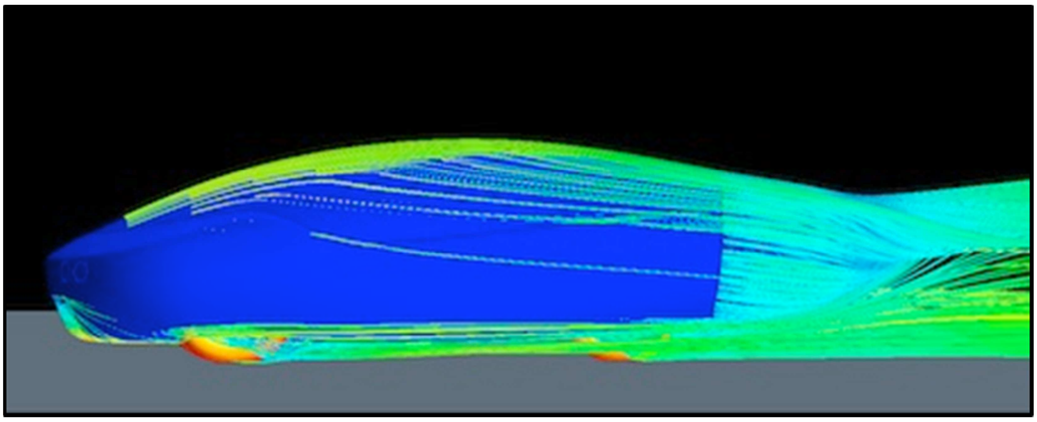

Figure 2 A simulation of Urbee’s aerodynamics (Kor Ecologic, 2014).

8.2.2 Building a Full-Sized Prototype

The first step in creating a full-sized prototype of the Urbee was to carve out a 60% scale clay model that could be scanned into CAD software to test its aerodynamic properties and further refine the specifications of its design. From there, a full-size prototype could be built based on the 3D digital model. It was clear from the start that traditional manufacturing methods would not be suitable for building a lightweight, highly efficient urban vehicle of the future (Kor, 2013b). The first potential alternative that was familiar to the team was the use of fibre-reinforced polymer (FRP) or fibreglass. However, the team wanted to have a working prototype much sooner than was possible with fibreglass panels, which would have required eight to ten months of steady work for two people to complete.

A second familiar alternative was rapid design prototyping with AM. Indeed, several global automotive suppliers and VMs already make use of AM for this purpose: creating tangible prototypes of individual parts and components quickly, cost effectively and accurately for testing purposes. The issue was that 3D printing had never before been used to prototype the full exterior body of a vehicle given that most commercial 3D printers at the time were unable to accommodate large objects. Fortunately, one of the team's designers came across Stratasys, a Minnesota-based manufacturer of 3D production systems that was on the forefront of developing 3D printing solutions for larger objects (Kor, 2013b). Confident that their design was correct and equipped with a 3D digital model, KOR Ecologic decided in 2010 to pursue 3D printing to rapidly prototype the Urbee in partnership with RedEye On Demand[22] and their largest performance series 3D production system: the Fortus 900mc fused-deposition modeling (FDM) 3D printer, shown in Figure 3 sitting to the left of a prototype of the Urbee (Bargmann, 2013; Stratasys, 2017).

Figure 3 Urbee sitting next to Stratasys' Fortus series FDM 3D printer (Stratasys, 2013).

Despite its ability to accommodate much larger objects, Urbee's body panels were still much too large for the Fortus 3D production system. The 3D digital model had to be divided into 20 strategically sized pieces and later assembled using dovetail joins (Bargmann, 2013). The first full scale prototype was 3D printed out of fully recyclable acrylonitrile butadiene styrene (ABS) plastic over about 2,500 hours and was just over three metres long (George, 2013). Once fabricated, the car's body panels were bolted onto a lightweight sub-frame made of alloy steel

[22] Stratysys' previous production arm, now called Stratasys Direct Manufacturing.

tubing that had been welded together (Kor, 2012a). Despite its ABS plastic exterior, KOR Ecologic claimed that Urbee's tubular sub-frame (Figure 4), which encapsulates the car's occupants, offers racecar-like safety similar to a roll cage (George, 2013). There is also the possibility of exploiting the flexibility of 3D printing to create shock-absorbing parts and crash structures placed between the printed exterior body and the metal sub-frame to further enhance Urbee's safety (George, 2013). Furthermore, Urbee's lightweight and three-wheel configuration means that it would likely be classified as a motorcycle in many jurisdictions, affecting the required crash standards.

Figure 4 Urbee's tubular, alloy-steel sub-frame (Kor Ecologic, 2014).

8.2.3 Urbee 2

After successfully creating a full-sized prototype and with newfound knowledge of the tremendous capabilities of AM, KOR Ecologic began planning the development of a second iteration of the Urbee in 2013 to maximize the unique advantages of the 3D printing process. The aim was to reimagine how vehicles are mass-produced by creating a much cleaner and compact "factory of the future" housing many 3D printers each capable of on-demand manufacturing (Kor, 2012b). The outsourced powertrain to be used in Urbee 2 was envisioned as being purely electric at city speeds (below 40 MPH or 64 km/h) using an ethanol powered ICE exclusively at higher speeds or in combination with the electric motor for more power when passing or travelling over steep terrain (Kor & Vukelic, 2011). The company had planned to make a historic and record-breaking journey in Urbee 2 in 2015 travelling from New York to San Francisco using only 10 gallons of bio-fuel; however, the journey has yet to take place following unsuccessful crowdfunding efforts (Millsaps, 2016). It appears that the Urbee 2 project has been stalled due to a lack of capital funding; the most recent media reports about Urbee 2 mostly date back to 2013. The fate of KOR Ecologic's Urbee car project is, therefore, currently unknown.

8.3 The Strati by Local Motors

8.3.1 Overcoming Barriers to Industrial-Scale 3D Printing

While the Urbee was the world's first vehicle to have a production-worthy 3D printed exterior shell, the vehicle in the second case study was the world's first vehicle to feature a fully 3D printed structure, integrating both the car's body and chassis into a single piece. As previously mentioned, one of the primary barriers to the application of 3D printing technologies in the automotive industry is the inability to print larger objects, as most commercial-grade 3D printers can only accommodate smaller objects with a volume of no more than 1,000 cm^3 (Babu et al., 2015). Despite the size advantages of the Fortus 3D production system used to print the Urbee, it too could not accommodate the body panels in full, requiring each panel to be divided into multiple pieces. As a result of the additional assembly, Urbee's 3D printed panels required more labour than the stamped metal panels traditionally used in automotive manufacturing (Richardson, Will, and Napper, 2015).

Size is not the only limitation that has helped restrict the use of AM technologies to specialized applications such as biomedical devices or the aerospace industry. Other fundamental impediments include build speed, which is typically less than 30 cm^3 per minute, and the cost of material feedstock, which is typically in the range of USD $100/kg (Babu et al., 2015). Arguably, the FDM 3D printing technology used by KOR Ecologic demonstrated all three of these limitations: the body was printed in multiple sections; approximately 2,500 hours of 3D printing was required; and it used a relatively expensive ultra-fine pre-processed ABS plastic filament (Georges, 2013). In order for AM to feasibly revolutionize the automotive industry, the three fundamental barriers of AM (size, speed, and material cost) would have to be addressed. American vehicle manufacturing company Local Motors (LM) hoped to demonstrate a radical new way of building lightweight, sustainable, and fully recyclable production vehicles that use far less material and require much less capital than traditional automotive assembly plants with the use of an innovative industrial scale 3D printing technology.

8.3.2 Disrupting the Auto Industry

John "Jay" B. Rogers Jr., co-founder and CEO of Local Motors, wanted to address the staggering amount of capital that is necessary to design and manufacture contemporary automobiles, a reality he claims stems from the fact that cars have been built much the same way since 1915; that is to say, thousands of individual components are put together along a moving assembly line (Dyer, 2015). Rogers believes the solution to this problem is to radically disrupt the way in which cars are built using industrial-scale 3D printing not just as a tool for rapid prototyping— already a common practice in the automotive industry—but to actually build final production vehicles. Local Motors describes itself as a technology company that not only designs, builds, and sells vehicles, but also prides itself on being much more than that. The company's manifesto proclaims that it is "loyal to local" and working towards a future where "supply and demand have the same hometown" by "disrupting the status quo" and "declaring the end of the large factory footprint" (localmotors, 2015, 0:16-0:30). The company wants to decrease the amount of expensive tooling required for automotive manufacturing and drastically reduce the launch time of highway capable vehicles using an innovative design process based on open innovation, which includes crowdsourcing and co-creation, and localized micro-factories enabled by direct digital manufacturing (DDM).

The purpose of a digitally enabled co-creation platform is to effectively and efficiently bring together designers, engineers, and innovators from around the world to collaboratively solve tough challenges in less time (Rogers, 2016). In September 2016, the company introduced a new digitally enabled open innovation platform called *Launch Fourth*, which they hope will reduce the development and launch cycle of their vehicles to six months or less. The goal of re-localizing manufacturing through 3D printing enabled micro-factories is to drastically reduce the capital costs required to build vehicles that are made up of far fewer parts to decrease the environmental costs associated with large-scale, centralized manufacturing. The "buy-to-fly" ratio in traditional automotive manufacturing is usually about twenty-to-one, meaning the weight of the raw materials used to manufacture a vehicle is 20 times more than the weight of the finished vehicle that rolls off the assembly line (Business Insider, 2015). By 3D printing entire vehicle structures, LM can achieve a buy-to-fly ratio that is very close to one, minimizing material wastes and dramatically reducing manufacturing costs. Somewhat emulating the road paved by Silicon Valley's open-source software, LM hopes to combine its crowd-powered co-creation approach with local micro-factories to develop a new generation of so-called “open hardware” (Rogers, 2016, 8:53). Although the company has already begun selling a Local Motors branded vehicle named the Rally Fighter, Rogers is open to the possibility of working as a supplier for larger OEMs (Dyer, 2015).

8.3.3 Developing an Industrial Scale 3D Printing Machine

The ground breaking technology that enabled LM to produce a continuous, 3D printed vehicle structure is known as Big-Area Additive Manufacturing (BAAM). The technology was developed by machine-tool manufacturer Cincinnati Incorporated in collaboration with the Manufacturing Demonstration Facility at the Oak Ridge National Laboratory (ORNL) in Tennessee with the funding support of the US Department of Energy’s Advanced Manufacturing Office (Manheim, 2014). The design and technology used to build the industrial sized 3D printer was based on Cincinnati’s laser cutting machine platform. The gantry-style setup was adapted with an automated material extruder and feeding system that allowed the system to be easily configured to an industrial scale capable of printing 8 feet in every dimension, in addition to offering several other distinct advantages over commercial 3D printing technologies (Babu et al., 2015).

In an effort to reduce the high production cost associated with the pre-processed polymer filament used in AM technologies like FDM, BAAM was designed to use commodity thermoplastic materials, specifically the same ABS plastic pellets used for injection molding (Love et al., 2015). Unfortunately, parts printed using this low cost (USD $1.40/kg) material experienced significant warping (Babu et al., 2015). Material trials determined that reinforcing the thermoplastic pellets with carbon fibre (CF) improved the material’s thermal properties, effectively reducing the level of distortion while also providing added strength and stiffness. For this reason, the Strati was made out of a more expensive CF reinforced ABS plastic (USD $25/kg). In order to scale-up the technology, BAMM had to address the rate of material deposition so that larger parts could be printed relatively quickly. Instead of melting a thin polymer filament to a semi-liquid state and extruding it through a tiny nozzle measuring only 250 micrometers, BAAM used a single-screw extruder with a five millimeter nozzle to accommodate the larger material feedstock. As a result, the flow rate at the end of the extruder is much faster (about 16,000 cm^3/min). Also, due to the relative size of the semi-liquid plastic beads deposited by BAAM's larger extrusion nozzle, they remain heated for several seconds after they have been deposited, allowing cross-links (a type of chemical bond linking polymer chains) to form between successive layers, creating a much stronger adhesion between them (Babu et al., 2015). These processing and material advantages allowed LM to scale-up the technology so that it could feasibly print an entire vehicle structure. Furthermore, BAAM uses an open-air design that is much more energy efficient than other AM technologies that require a heating chamber to maintain strict environmental controls throughout the printing process (Babu et al. 2015).

Figure 5 A prototype of LM's first 3D printed car, the Strati (Stains, 2015 in Dyer, 2015).

8.3.4 A Live Demonstration of Local Motors' 3D Printing Technology

The world's first vehicle to combine both co-creation and DDM is called the Strati (Figure 5), the winner of LM's first ever 3D Printed Car Design Challenge, by Italian automotive designer Michele Anoé (LM, 2014). The company had received more than 200 submissions during the six-week challenge, which culminated in a live demonstration at the International Manufacturing Technology Show (IMTS) 2014 in Chicago, Illinois. The live-build demonstration was used to debut the Strati and its innovative, industrial scale 3D printer. The process began with 44 hours of additive manufacturing to create the structure of the vehicle upon which the rest of its approximately 40 components (Figure 6) could be rapidly assembled, including the motor, wheels, suspension, seats, and windshield, by a small team before the functional prototype took its historic first drive off the showroom floor within the six day time frame of the event. The Strati, a small rear-wheel drive, two-seater convertible with a retractable roof, features a single, continuous 3D printed structure incorporating the exterior body, seat molds, door panels, and chassis. The components that were not 3D printed include a lightweight aluminum sub-frame in the rear to support the electric drivetrain (i.e., battery and electric motor) and suspension, which were borrowed from the Renault Twizy urban EV (Pyper, 2014; U.S. DOE AMO, 2014).

Figure 6 Strati's dematerialized design is amenable to rapid manufacturing (Lecklide, 2017).

Portions of the vehicle were milled using subtractive manufacturing to smooth out their appearance while others were left untouched to display how the layers of CF reinforced polymer appear right out of the printer as shown in Figure 7 (Dyer, 2015). Rogers says that the exterior of the vehicle could be made to look exactly like what a customer envisioned, and could even be covered in a vinyl wrap without affecting its recyclability. An advantage of having a fully 3D printed structure is that in the case of catastrophic damage, the drivetrain and mechanical components can be removed, the structure can be melted down into pellets and fully reprinted, prolonging the life cycle of the vehicle's most expensive components like its battery and drivetrain. The use of AM could also enable new approaches to automotive safety including embedding energy absorbing crash structures or anchoring seat belt mounts deep inside the car's structure (Dyer, 2015). Local Motors is also experimenting with new bumper materials to cushion pedestrian impacts, including an elastic polyurethane. It should be noted that the current prototype is a proof of concept that has not yet been equipped with seat belts or been crash tested by federal regulators.

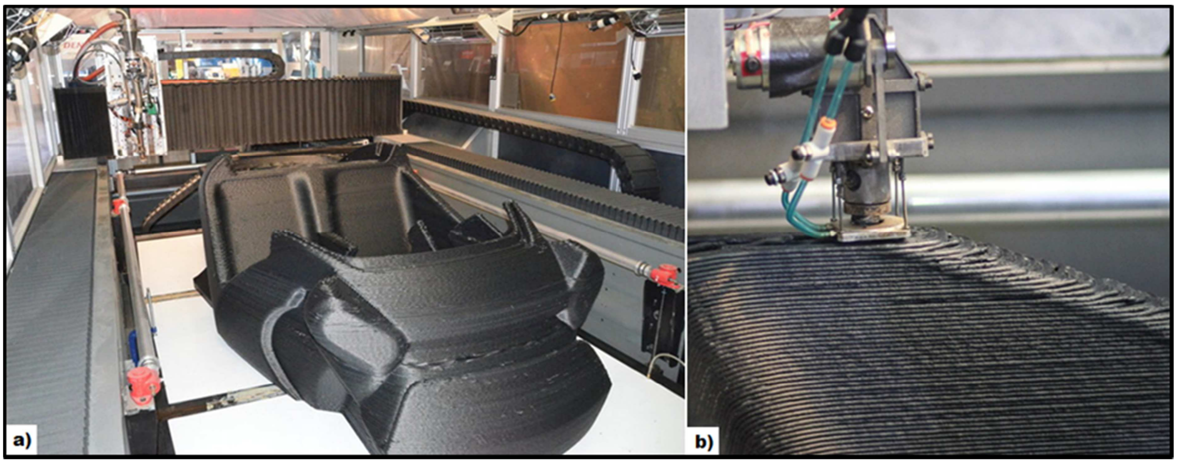

Figure 7 a) Strati being 3D printed inside a BAAM machine (Bhatia, 2016) and b) A close up of the extrusion nozzle displaying the untouched layers of material (Warren, 2015).

8.4 The Blade by Divergent 3D

8.4.1 Addressing Life Cycle Emissions with 3D Printing

The final case study features Divergent 3D[23], a manufacturing technology company that "is dedicated to revolutionizing car manufacturing and reducing its environmental impact on the planet" by addressing life cycle vehicle emissions using an innovative 3D metal printed vehicle platform (PSA & Divergent3D, 2016). The founder and CEO of Divergent 3D, Kevin Czinger, previously attempted to disrupt the automotive industry and reduce transport related GHG emissions by co-founding the small electric-car company Coda Automotive. Czinger, however, came to the realization that if Coda were to ever successfully scale-up its business and mass produce a BEV, the technology would still result in significant environmental destruction as a result of the carbon emissions from the vehicle's manufacturing process, including the extraction of virgin resources and all input materials (Czinger, 2015c; Rosenblum, 2015). Although BEVs do not emit GHG emissions while in use, they are responsible for emissions associated with their manufacture and electricity generation. Czinger realized that if the way BEVs are produced remains the same as conventional ICEVs, then the environmental damage and GHG emissions resulting from their manufacture would not just remain the same but in fact worsen due to the

[23] The company was originally named Divergent Microfactories.

material intensity of battery production. With a newfound understanding of life cycle emissions, Czinger stepped down from his role at Coda Automotive in 2010[24] and refocused his efforts at Divergent 3D, where he would attempt to curtail the economic and environmental costs associated with contemporary vehicle manufacturing (Rosenblum, 2015).

One of the founding inspirations for Divergent 3D was a report published by the National Academy of Science (NAS) in 2009 titled *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*. The report was one of the first of its kind to conduct an in-depth analysis of the life cycle emissions of light-duty vehicles powered by various fuel types and monetize their impact on the environment and on human health (Czinger, 2015c). The report reinforced Czinger's belief that cars could—and in fact should—be better and be built in a more environmentally sustainable manner (Czinger, 2015b; Divergent 3D, 2016).

Figure 8 Divergent 3D's Blade 3D printed supercar (Divergent 3D, n.d.).

Divergent's idea was to disrupt automotive manufacturing by replacing the dominate production technology that has led to cars getting larger and heavier, and subsequently less efficient over time. Divergent adapted the methodology used by the NAS to highlight the reduction in life cycle emissions that are possible with their innovative vehicle concept, named the Blade and touted as the world's first 3D printed supercar, compared to ICEVs, HEVs, and BEVs. The company used the results to promote their philosophy for sustainable automotive manufacturing and its superiority over the status quo and other possible alternatives (e.g., mass

[24] Coda Automotive filed for bankruptcy in 2013 and has since rebranded to focus on energy storage applications in commercial and industrial settings under the name Coda Energy (Weiss, 2015).

produced EVs). The Blade (Figure 8) is a sleek looking supercar boasting 700 HP and can supposedly accelerate from a full stop to 60 MPH in just 2.5 seconds. Therefore, the company suggested that future vehicles based on their innovative technology could produce even less damage to environmental systems and to human health (Hafemeister, 2015). The importance of Divergent's life cycle assessment is to justify its strategy of pursuing manufacturing innovation to reduce vehicle related carbon emissions rather than focusing merely on powertrain innovations such as electrification, which primarily addresses use-phase emissions while ignoring the environmental damage that stems from the rest of the vehicle's life cycle including its production, which has been shown to be higher for PEVs.

8.4.2 "Dematerialization through Democratization"

Divergent's strategy differs somewhat from the previous two case studies, which incorporated small electric powertrains with a lightweight 3D printed body and structure, respectively. The core innovation at Divergent 3D is a flexible, modular vehicle chassis enabled by 3D metal printing. Divergent's disruptive philosophy is to dematerialize vehicle production (i.e., reducing its material and energy requirements) by democratizing it (i.e., making it affordable and accessible) to reap the maximum benefits from local ingenuity and innovation (Czinger, 2015a). Divergent hopes to democratize auto manufacturing to foster local innovation by lowering entrance barriers with tools and technologies that are accessible and affordable to small teams of entrepreneurs around the world who can build cars tailored to the needs and tastes of local populations (Czinger, 2015a). One of Czinger's inspirations for democratizing manufacturing was his experience "hot-rodding" a 1968 Plymouth Barracuda alongside his brothers using what he described as "shared ingenuity and hard work" to overcome their lack of money and building something that was functional through continuous improvements and modifications—essentially executing "the rapid versioning of hardware" (Czinger, 2015a). With Divergent 3D, Czinger hoped to bring a similar spirit to the one he experienced growing up back to the automotive industry—in a controlled manner— and making it more easily accessible.

Czinger's vision was to develop a flexible and modular "technology platform" upon which small teams of people without the typical expertise required for car manufacturing could use to build a vehicle and realize true mass customization (Czinger, 2015a). Czinger envisioned adopting the strategy used by Arduino, "an open-source electronics platform based on easy-to-use hardware and software", to lower the barriers to entry and empower local producers through an industrial strength Arduino for cars or "carduino" (referring to Divergent's technology platform) by similarly hiding its underlying complexity behind a simple, easy-to-use interface (Arduino, 2017; Czinger, 2015a).

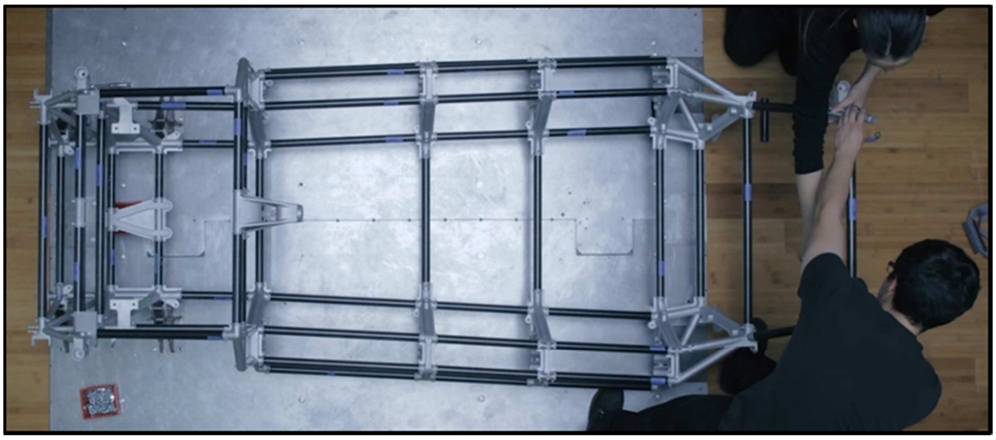

Figure 9 Divergent's first proprietary platform with 3D printed metal nodes and CF tubing (Business Wire, 2016).

The tool that Divergent engineered to achieve its goal of dematerializing and democratizing manufacturing is an innovative, DIY platform made of 3D metal printed components (Figure 9) that could be easily and quickly put together in a small-scale, capital-light micro-factory equipped with 3D metal printers rather than expensive tooling (Rosenblum, 2015). Czinger (2015a) says its globally dispersed micro-factories could be built for between USD $20 million to USD $50 million including printing and assembly equipment, as much as 50 times less expensive than a traditional high volume automotive assembly plant that costs in the vicinity of USD $1 billion to build. By removing the substantial capital barrier associated with the current automotive paradigm, Divergent 3D hopes its design philosophy and patented platform technology will empower local small-batch carmakers around the world to "design solutions that are relevant to their local communities" (Czinger, 2015b).

Divergent 3D's ambitions to dematerialize and democratize the automotive industry with local and small-scale micro-factories are congruent with the main principles of MFR. A fundamental requirement of the MFR model and its goal of lowering the cost of entry into automotive manufacturing was that the production technology of the existing paradigm could not persist. If Divergent 3D's vision comes to fruition, they just might be on the path towards developing a feasible alternative technology that could enable a transition towards MFR. Another one of Czinger's "ten principles for sane manufacturing" is to "treat 'making' as an art" by innovating and engineering the process of making a product as much as the product itself and to use manufacturing innovation to elevate creativity and human capital rather than focusing on manufacturing efficiency for the purpose of commoditizing (Czinger, 2015a).

Figure 10 Divergent's proprietary 3D metal printed structural node (Divergent 3D, n.d.).

8.4.3 The Divergent Manufacturing Platform™

The key technology enabling Divergent's modular vehicle platform that the company hopes will revolutionize automotive manufacturing is an innovative aluminum alloy connector called a "node" (Figure 10), and made using a 3D metal printer that uses lasers to fuse together metal powders. These nodes are essentially used as Lego blocks to join together CF tubing. The platform that underpins the Blade can be assembled with epoxy by only two people in as little as 30 minutes and weighs only 61 pounds, which is 80 to 90% lighter than a traditional vehicle chassis (Rosenblum, 2015). In a similar manner to Arduino's electronics platform, Divergent's 3D node technology masks its inherent complexity by realizing the efficiencies inherent with 3D printing (Czinger, 2015a). Divergent has exercised its engineering expertise to develop the complex structure of its nodes to enable a flexible platform that offers end users a simple, easy to use interface upon which they can place a variety of different, highly personalized body designs without any additional cost (Czinger, 2015b). Furthermore, the size of the 3D printed nodes means they do not require industrial-sized 3D printers and can instead rely on innovative 3D metal printing technologies.

Unlike the two previous vehicles, Urbee and Strati, the Blade does not use a 3D printed exterior body to replace the industry's expensive and time consuming stamped metal body panels but rather, makes use of aerospace-grade CF shearing. Czinger claims these body panels could be produced for less than USD $1,000 and the CF could be submitted for alternative materials to further reduce the vehicle's weight, such as Kevlar or spandex (Rosenblum, 2015). The disruptive power of the Divergent Manufacturing Platform™ is in its flexibility and ease of assembly. The platform can easily be adjusted to suit different body styles from a two-seater tandem sports car (i.e., the Blade) to a pick-up truck or any other vehicle segment by simply adjusting the length of the CF tubes (Czinger, 2015b). Such flexibility will allow Divergent's platform technology to underpin a range of vehicle types depending on local needs and tastes.

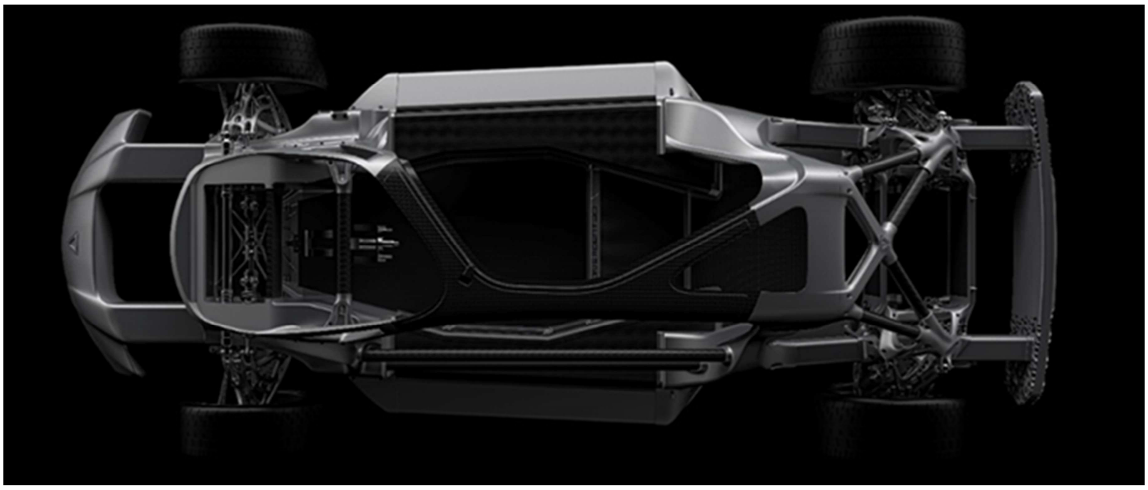

Figure 11 The latest iteration of Divergent's manufacturing platform (Divergent 3D, n.d.).

The Blade first debuted as a concept in 2015, while the car remains a "proof-of-concept" in its latest iteration (unveiled at the 2017 Consumer Electronics Show) it was endowed with significantly more 3D printed components, including a new aluminum and titanium frame (Figure 11), and crash structures and suspension assemblies—looking substantially more "high-tech" (Orlove, 2017). The design flexibility enabled by 3D printing allows components, like the

Blade's suspension assembly, to be optimized for weight and strength, resulting in unusual and organic looking shapes as seen in Figure 12.

Figure 12 The Blade's 3D metal printed suspension assembly (Divergent 3D, n.d.).

The Blade uses a custom, mid-mounted bi-fuel 2.4 litre turbocharged 4-cylinder engine outsourced from an external supplier to give the lightweight Blade (1,400 pounds or 635 kg) supercar performance while maximizing fuel efficiency (Rosenblum, 2015; Silvestro, 2017). However, a variety of different powertrains could be fitted to the platform, meaning it could underpin a zero-emission battery electric powertrain in regions with renewable energy generation. Alternatively, in regions where coal power plants exist, vehicles with efficient ICEs could be used to reduce the overall environmental damage of the vehicle.

8.4.4 Divergent's Business Model & Strategic Partnerships

The Blade was built to demonstrate the feasibility and functionality of Divergent's proprietary manufacturing platform. However, Divergent 3D does not intend to be in the car making business, instead describing itself as a technology company focused on partnerships with other companies—whether they be global OEMs or small micro-factories—to allow them to build lightweight, efficient, and sustainable vehicles based on their innovative software-hardware platform (Divergent 3D, 2016b). French automaker PSA has publicly released a letter of intent to engage in a strategic partnership with Divergent 3D in the hopes of "charting a new future of dramatically more efficient automobile manufacturing" (PSA & Divergent3D, 2016). The PSA Group plans to explore the implementation of Divergent's proprietary production technology (the Divergent Manufacturing Platform™), which radically transforms the economics and environmental impact of vehicle design and manufacture, so that PSA can become a global leader in efficient automotive manufacturing (PSA & Divergent3D, 2016). By altering the overall structure of its vehicles to accommodate the innovative design and manufacturing process of Divergent's 3D printed platform, PSA hopes to build vehicles that are lighter and structurally safer than conventional automobiles, and that are more efficient and sustainable. The technology could also be used to dramatically scale down PSA's manufacturing footprint by reducing build complexity while simultaneously allowing for a near limitless level of design flexibility. Such radical changes, if achieved, could position the PSA group and Divergent 3D as leaders in the future of sustainable automotive manufacturing.

Furthermore, Divergent announced in January of 2017 that it has raised USD$23 million in venture capital[25] to commercialize its innovative manufacturing platform (Divergent, 2017). As part of this goal, Divergent 3D has entered into a strategic development partnership with SLM Solutions Group[26]. By deepening their existing cooperation into a long-term partnership, the companies hope to create a vehicle construction that is more sustainable, flexible, and cost efficient by developing specialized and exclusive hardware and software to for use in industrial-scale mass production to further reduce time-to-market (SLM Solutions, 2017). Divergent 3D has also entered into a partnership with engineering research and development firm Altran to accelerate the commercialization and licensing of Divergent's Manufacturing Platform (Divergent3D, 2016a). Partnerships such as these will allow Divergent to further develop its patented platform, which fundamentally transforms the basic design, engineering, manufacturing, and assembly of modern vehicle structures, and empower automakers—like PSA—to cost effectively build vehicles that are more efficient and sustainable.

8.5 The Benefits of 3D Printing for Production Vehicles

8.5.1 Enabling Sustainable Design with 3D Printing

Urbee's unique and highly efficient design was made possible by 3D printing and its ability to create complex structures that optimize both strength and weight, important considerations for safety and fuel efficiency. Current production technologies, including injection molding and sheet metal stamping, offer less design flexibility and require dedicated

[25] The Series A funding round was led by technology venture capital fund Horizon Ventures

[26] The German-based company is a leader in manufacturing metal-based 3D printing equipment.

tooling that is both costly and time consuming to build and install. Prior to the recent advancements in AM, these methods were considered to be the only means of mass producing low cost vehicles thanks to the significant economies of scale that can be achieved with these technologies (Kor, 2012a).

Despite short-term economic gains over periods lasting up to several decades, when analyzed over longer timescales, such a millennia, the economics of traditional manufacturing methods are less favourable when accounting for environmental externalities including an "enduring legacy of waste" and the resulting degradation to nature (Kor, 2012b). This is no truer than in the automotive industry. Additive manufacturing removes the need for dedicated tooling and is able to print whichever parts are needed whenever they are needed in a process that is fully automated and on-demand. The precise control and design freedom available with 3D printing means that complex structures can be optimized in ways that are not possible when using sheet metal to reduce vehicle weight. For instance, with AM certain sections of the bumper could be made thicker than others adding additional strength and rigidity to areas where it is needed most and reducing the weight of parts overall (George, 2013). Another strategy Kor Ecologic plans to use on the second iteration of its design (dubbed Urbee 2) is to reduce the vehicle's overall complexity by replacing structures that would traditionally incorporate dozens of plastic and metal components into a single larger component made out of 3D printed thermoplastic (George, 2013). A dashboard, for instance, could be printed with the ducts already attached, removing the need for any joins and/or connecting parts. This reduces overall complexity and reduces material usage and resource intensity.

Jim Kor believes that when paired with related technological fields, digital AM has the power to provide an unparalleled level of flexibility, liberating designers to consider all possible solutions to a problem: solutions that would otherwise not have been possible. Along with AM, simulation software, high-performance computing (HPC), and biomimicry (a concept first introduced in Chapter Two) could enable far more sustainable designs (Kor, 2012c). By leveraging the capabilities of HPC and simulation modeling software, essentially all possible design alternatives could be tested in advance to determine optimal material compositions, shapes and structures, and production processes (Kor, 2012a). By quickly and accurately modeling a large number of alternative scenarios ahead of time, the first physical prototype of a product would likely be quite close to the final design specifications. Creating physical prototypes using traditional methods is not only time consuming but would be prohibitively expensive, limiting the number of possible alternatives designs that can be tested. Kor Ecologic was able to use both HPC and simulation software to optimize the aerodynamics of its vehicle prototype and to improve the vehicle's overall design to meet or exceed all required safety standards.

Jim Kor has said that Urbee's design was inspired by biomimicry citing natural inspirations such as the way cheetahs and falcons both manipulate their shape to become more aerodynamic when they want to increase their speed (Bargmann, 2012). Another nature-inspired design possibility for Urbee 2 is honeycomb shaped structural infill for its 3D printed ABS plastic body panels. The closed geometry of honeycomb means that it is a highly efficient by nature; its structure optimizes weight reduction with material use and it cannot be recreated using traditional techniques like stamping and injection molding (Richardson et al., 2015). Beukers & Hinte (as cited by Kor, 2012, p. 6) argued that honeycomb's complex structure has been perfected by nature to be light yet strong and incredibly efficient: "any lesser structure would require greater effort and more resources" to create, suggesting honeybees have achieved the delicate harmony between material, shape, and production process involved in constructing for lightness. Design flexibility and biomimicry also influenced the structure and shape the 3D printed components found on the Blade, including the extraordinary shapes found in its suspension assembly. Czinger insisted that this complexity, enabled by 3D printing, is the result of optimizing the weight and strength of each component, suggesting there is simply no other shape that is both lighter and stronger (Orlove, 2017). The ability of 3D printing to produce highly complex and elaborate structures without any addition cost is one of its greatest advantages. Essentially, any additional complexity is free allowing parts to be optimized for their intended use and purpose. Additive manufacturing could enable more sustainable designs inspired by complex nature structures that were previously not possible to recreate using traditional manufacturing methods.

8.5.2 Reduced Complexity and Dematerialization

One of the fundamental goals of LM is to drastically reduce the overall complexity associated with contemporary automobiles and their manufacturing process. Conventional automobiles manufactured using traditional methods can contain up to 20,000 individual parts that have been assembled together at some point during the fabrication process creating significant complexity and many opportunities for errors and malfunctions to occur (Babu, 2015). By vastly reducing the number of parts required to build a vehicle (as few as 50) through AM and an electric motor with fewer moving parts, LM hopes to drastically reduce the cost and complexity of the next generation of automobiles. Costing between USD $5,000-$7,000 to produce, a vehicle like the Strati could be used to bring low cost, locally manufactured, and sustainable transportation to developing countries (Dyer, 2015). Alternatively, the same model could be used to offer high-end buyers who value personalization to build a fully customizable vehicle printed in an individual production run. Although Rogers admits that there will likely still be room for mass market VMs in the automotive ecosystem, DDM allows low volume manufacturing to be profitable, unlike current production technologies that depend on economies of scale to drive down unit costs (Figure 13).

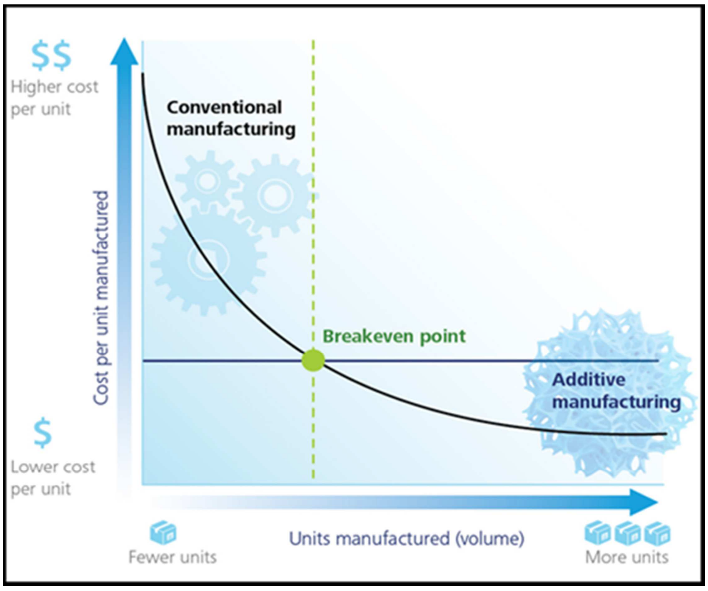

Figure 13 A unit cost comparison of conventional and additive manufacturing based on production volume (Cotteleer & Joyce, 2014).

Dematerialization is associated with many other environmental and societal benefits as well. The thousands of parts and components that go into a typical automobile create material waste and generate GHG emissions during their manufacturing process, while generating additional emissions because of long logistics chains used to ship finished parts from a global network of suppliers to a centralized facility for final assembly. From there, finished vehicles must be transported—sometimes over long distances—to the location where they will eventually be sold and where their ICE will release emissions throughout its lifespan. Collectively, life cycle GHG emissions, resource depletion from manufacturing, and air pollution from driving ICE vehicles contribute to the automotive industry's externalized costs to the environment.

Divergent hopes that its dematerialized, ultra-lightweight vehicle platform that uses significantly less material and energy inputs will allow it to build vehicles that are greener, lighter, and safer than the vehicles on the road today. Dematerialization addresses the high material and energy use associated with existing automotive manufacturing methods while also allowing cars to use smaller, more efficient engines to reduce tailpipe emissions. Furthermore, light vehicles made using fewer components and less material could have additional positive effects such as reducing the wear on roadways, and reducing the severity of traffic accidents and potentially resulting in fewer fatalities (Czinger, 2015a).

8.6 Limitations and Barriers to 3D Printed Production Vehicles

It is worth noting that AM technologies are not intended to replace all automotive assembly processes. Even MMAM could not be used to completely print a finished vehicle. Said differently, a 3D printer and multi-material 3D printers could not create a fully functional production vehicle on their own without any additional assembly. The advantage of these technologies is to combine smaller parts into larger modular components to drastically reduce the overall number of parts and components that require assembly. In turn, the time and money required to build a vehicle is reduced.

Due to the unproven nature of 3D printing technology for use in building production vehicles or even building final parts for production vehicles, established OEMs may be hesitant to invest too heavily in the technology until there is evidence that the technology can in fact be profitably scaled-up to an industrial magnitude to achieve desired production volumes. As Rogers (CEO of LM) acknowledges, mass production automakers will likely maintain their influence within the wider automotive ecosystem for some time.

Another major roadblock that could delay the adoption of this technology is the question around safety and whether cars produced in this manner will be able to meet current regulated safety and crash standards. Specifically for early adopters of this technology, a potential risk could be an accident between a first generation 3D printed vehicle and a traditionally manufactured all-steel bodied vehicle. Even if these vehicles are shown to be as safe as or safer than conventional vehicles, if consumers are not convinced then the technology is unlikely to diffuse quickly. This leads to the fundamental question of demand and whether or not consumers will be open minded enough to purchase such a radical new vehicle design. The barriers facing EV were detailed in an earlier chapter and it is entirely reasonable to expect vehicles produced with 3D printed and using an electric powertrain to face a similar plethora of barriers from mainstream consumers.

As discussed in the chapter on AM, some technological barriers remain that must be resolved before this technology is ready to truly replace existing manufacturing technologies in the automotive industry. However, the history of 3D printing is one of constant evolution and development. Therefore, it is possible that this technology will feasible for full-scale automotive production sooner than what some OEMs might be anticipating.

Chapter 9 Discussion

9.1 The Probability and Timeline for Transition in the Automotive Industry

There is growing awareness that deep-structural changes are necessary if meaningful reductions in GHG emissions, required by tightening environmental regulations, are to be achieved in the transport sector (Arranz, 2017; Vaz, Rauen, & Lezana, 2017; Geels, 2012). The transport system is one of the few industrial sectors to record net increases in CO_2 emissions despite experiencing incremental improvements in efficiency and adopting new cleaner technologies. Efforts to reduce GHG emissions have been counterbalanced by increased consumption (i.e., higher vehicle sales) and intensity (i.e., longer and more frequent trips; Vaz et al., 2017). This "rebound effect" indicates that long-term sustainability goals are unlikely to be achieved through product or process level innovation, suggesting instead the need for larger scale, systemic change. Although this thesis focuses on both product and process innovations in the form of AM and EM respectively, they are not lauded as being "silver bullets" capable of solving the industry's sustainability crisis; rather, they are being put forth as a means to facilitate system level change through business model innovation in the form of PSS and a shift to a more environmentally and economically sustainable consumption and production paradigm in the form of MFR.

As such, there has been a growing interest in understanding the processes of socio-technical transition and system innovation for their potential to achieve much greater eco-efficiency gains through radical, rather than incremental, innovation and change (Geels, 2005). The significance of socio-technical systems with respect to lock-in and path-dependence (both of which have acted as barriers to technological innovations such as AM and EM, and to an extent, business model innovation) has been explored within the thesis. Similarly, a socio-technical approach can be applied to system-wide changes or transitions, providing a multi-disciplinary framework that is appropriate for analyzing "complex problems of unsustainability" and that has previously been applied to issues in the transport and mobility sectors among others (Whitmarsh, 2012, p. 483). Conceptualizing the transport sector as a socio-technical system yields a series of interrelated elements that together contribute to its structure and function: The transport sector can be divided into technology; policy and regulation; markets; consumer practices; infrastructure; maintenance and supply networks; cultural meaning; and scientific knowledge (Geels, 2012; Geels, 2005). Various individual actors—or groups of actors—have the ability to either maintain, reproduce, or change the elements that make up a socio-technical system, including firms and industrial actors; policy makers and politicians; consumers; social groups; and researchers (Geels, 2012). Systemic change therefore relies on the complex network of interactions between the elements that make up a socio-technical system and its stakeholders.

System innovation occurs when a socio-technical system transitions from one system to a new—and preferably more sustainable—system. Societal functions (e.g., transport and mobility) are fulfilled by socio-technical systems which are often "locked-in" along multiple dimensions due to the complexity of interactions that exist between the elements of the regime and the incumbent stakeholders that often have a vested interest in upholding it (Geels, 2005). Such systems can therefore often be characterized by a "dynamic stability".

Transition or system innovation are considered to be co-evolutionary processes due to the complex and multi-dimensional interactions that are involved requiring the simultaneous participation of multiple actors and social groups to overcome the existing regime's dynamic stability and often unfolding over decades (Geels, 2012). Researchers are keen to understand the dynamics of system innovation to determine, for instance, how a transition to low-carbon innovations can be stimulated or accelerated to improve the sustainability of societal functions (Whitmarsh, 2012).

9.1.1 A Framework for Studying System Innovation

The multi-level perspective (MLP) is a heuristic framework used to analyze the structure and dynamics of socio-technical systems and their multi-dimensional interactions according to Geels (2012), as well as a useful "analytical tool for identifying and engaging with diverse stakeholders groups" according to Whitmarsh (2012, p. 484). Within the transport literature, Whitmarch (2012, emphasis in original) found that the MLP has been used as an analytical tool for *understanding transition* and potential innovation pathways (Nykvist & Whitmarch, 2008); as a tool in modeling studies to identify future political, social, or economic levers that might *stimulate sustainable transitions* (Whitmarsh & Wietschel, 2008; Köhler et al., 2009); and as a tool for *stakeholder analysis* to identify actors within the various levels of the hierarchical framework (Whitmarsh, Swartling, & Jäger, 2009). The MLP, originally developed by Rip and Kemp (1998) in the field of innovation studies, has also relied on insights from other disciplines including evolutionary economics, sociology of technology, and neo-institutional theory (Geels, 2012).

The MLP identifies three analytical and heuristic levels used to conceptualize the dynamic and nonlinear process of transition: niches (micro-level), regimes (meso-level), and landscapes (macro-level). Together they form a nested hierarchy (Figure 14): niches are embedded within larger regimes, which are influenced by an overarching landscape (Geels, 2002). Niches are described as "the locus for radical innovation", while socio-technical regimes are described as "the locus of established practices and associated rules" that are embedded within dominant institutions and technologies (Geels, 2012; p. 472). Niches represent protected spaces where novelties emerge and where the seeds of systemic change are planted by niche-actors who have cultivated innovation, hoping that it will—at some point—be used alongside or replace technologies within the existing regime. Both AM and EM exists within the current regime at the niche level as they have yet to break into the mainstream. Similarly, innovative business models in the form of integrated PSS have yet to fully break into the existing regime despite the initial success of disruptive mobility companies like Uber and Lyft, which have faced significant resistance from established incumbents and institutional structures.

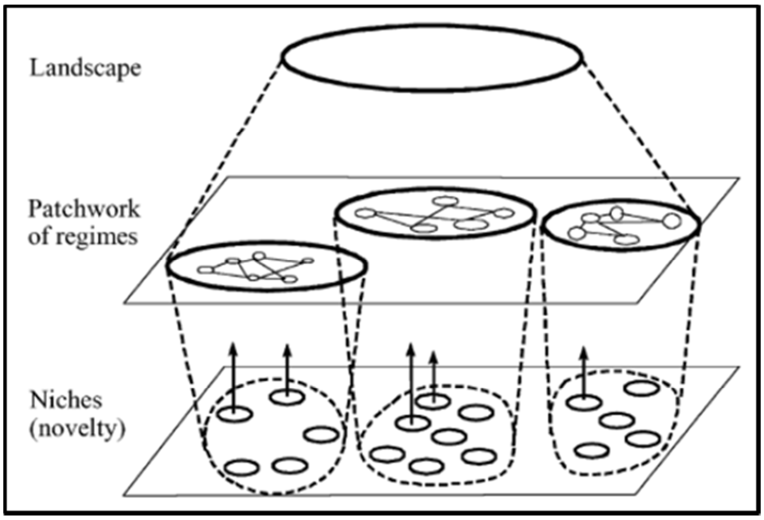

Figure 14 The MLP's Nested hierarchy (Geels, 2002, p. 1261).

At the top of the MLP is a socio-technical landscape, which encompasses the wider contextual factors that either promote or hinder change, and influence the dynamics of both regimes and niches (Geels, 2012). This wider context includes exogenous elements such as infrastructure; governments and regulatory systems; societal values, beliefs, concerns and norms;

cultural meanings; etc. (Kemp, Avelino, & Bressers, 2011). (For a more detailed description of each level of the MLP refer to Geels, 2012, p. 472-473). System innovation depends on the complex interactions between the dynamics at each level. Several phases can be identified throughout socio-technical transitions (Geels, 2005; Rotmans & Kemp & Asselt, 2001). In the first phase, new technologies or business models emerge in niches, embedded within the existing regime and subject to developments at the broader landscape level. During the second phase of transition, the dominant design and/or functionality of innovations are gradually improved and validated through processes of learning and user feedback in niche markets, to create a technological trajectory (Geels, 2005).

In the third phase, niche-level innovations breakthrough the existing regime to compete directly against mainstream technologies because of several processes acting at the niche and regime level. At the niche level, internal factors like improved functionality or price signals can drive the adoption of an innovation and increase its competitiveness. At the regime level, "windows of opportunity" are created when external landscape pressures (e.g., stricter regulations and changing user preferences) or internal problems affecting the existing technology (e.g., negative externalities) reduce its competitiveness and the overall stability of the regime.

In the fourth phase, the innovation successfully replaces the dominant technology to create a new socio-technical regime that over time can influence the socio-technical landscape. Transitions often progress slowly due to resistance at multiple levels. Previous investments and vested interests in the existing regime often contribute to lock-in and path-dependence (Geels, 2005). The MLP provides a mechanism for assessing the complex processes involved throughout the transition process (Geels, 2012).

9.1.2 Routes for System Innovation

Geels (2012) describes two potential routes for system innovation. The first is called the "technological substitution route" and is characterized by the sudden breakthrough of a novel technology that has slowly matured at the niche level, gaining momentum through gradual improvements. Along this route, innovations can go relatively unnoticed by dominant regime-actors as they "smoulder below the surface" of the regime. In the presence of enough internal momentum or technological push at the niche level and top-down pressures from the landscape onto the regime, a technology can suddenly breakthrough the regime and into mainstream markets, taking some regime-actors by surprise. The breakthrough can give rise to the reorganization or restructuring of the existing regime, potentially leading to creative destruction and the failure of incumbent firms. Once a new socio-technical regime has been established, the regime dynamics return to processes of incremental change and dynamic stability.

It could be argued that if AM continues its rapid development, it could gain enough internal momentum to overcome the lock-in of traditional manufacturing technologies and potentially replace Budd-style all-steel car bodies via technological substitution. Although AM is present within the current regime, it is used exclusively for rapid prototyping rather than for final production parts. If, for instance, global OEMs fail to recognize the potential utility of AM for final production parts, niche-level actors (like the entrepreneurial firms studied in this thesis) could spearhead developments in AM, generating internal momentum to break through the dominant regime and potentially taking unsuspecting incumbents by surprise. In this scenario, barriers to AM would be overcome at the niche level by smaller firms while regulatory, economic, market, and environmental factors at the landscape level would continue to put pressure on the dominance of existing manufacturing technologies, potentially creating a window of opportunity for AM to enter mainstream markets. Provided that it was competitive against existing technologies, AM could foreseeably replace the existing regime through system innovation. Such a scenario could be the basis of future research using the MLP.

The second route described by Geels (2005) is called the "wider transformation route" which arguably could be said to describe the emergence of EM within the current regime. In this route, the existing regime becomes unstable at an early stage as a result of persistent landscape pressures and/or internal regime problems (e.g., policy, user preferences, technology, infrastructure, culture, etc.). Simultaneous changes occurring at multiple dimensions promotes exploration and experimentation among regime-actors searching for an alternative technology. Such a period of strategic maneuvering can be fairly protracted, eventually concluding in a period of selection to narrow the list of potential alternatives. Regime actors are often fearful of "picking a winner" in case they choose an alternative that does not diffuse in the market as quickly as anticipated. Once a particular alternative is considered universal, having been collectively selected, it may begin to push-aside competing technologies and come to dominate within a new socio-technical regime.

The resurgence of PEVs within the current regime resembles the wider transformation route. Apart from competing with new, more efficient ICE technologies, PEVs are also competing with other novel low-carbon technologies including hybridization, hydrogen fuel, and bio-fuels. Although some OEMs offer hydrogen fuel-cell vehicles (HFCVs), collectively the industry has arguably—willingly or unwillingly—selected PEVs due to pressure from within the regime and at the landscape level including consumer preference, regulations, and infrastructure. Hydrogen fueling stations lag even further behind public charging infrastructure and unlike PEVs, HFCVs cannot be refueled at home.

Although there has yet to be a full-scale transition towards EM, there are signs that such a transition is in its early stages. Unlike the technological substitution route, a transition towards EM is likely to occur gradually as consumer preferences adjust and public charging is expended. However, recent commitments by global OEMs to market an increasing number of PEVs, tightening emissions and fuel economy regulations, plans in some jurisdictions to ban the sale of ICEVs, and increasing levels of adoption all suggest that a transition towards mainstream EM has begun, a remaining question is: How long it will be before PEVs actually outcompete ICEV to form a new stable regime?

9.1.3 Patterns of Technological Breakthrough

Geels (2005) also distinguishes several patterns that can emerge during the breakthrough of a novel technology. Some of the identified patterns were particularly relevant to the technologies proposed in this thesis. Several patterns in the co-evolution of technologies were distinguished, including the concept of complementarity between technologies. Complementary relationships between technologies become important "when the functionality of a new technology is hampered by particular constraints and problems, the linkage with another technology may solve them and boost performance and diffusion" (Geels, 2012, p. 692). This sort of interaction was alluded to when discussing potential synergies that could be leveraged between AM and EM and business model innovation (i.e., PSS and MFR). For instance, the potential for AM to reduce the weight and complexity of automotive bodies could benefit the diffusion of PEVs by extending their range, an often-cited barrier to adoption. Furthermore, innovative business models based on integrated PSS could benefit the adoption and use of PEVs by changing patterns of ownership and use to overcome adoption barriers.

A core concept in this thesis is the potential of AM to replace traditional manufacturing techniques and the all-steel car body. Such a transition would create a window of opportunity for new business models in the form of PSS but also for entirely new patterns of manufacturing as proposed by MFR (i.e., small-scale, localized manufacturing). The MLP could provide a means for more accurately assessing potential synergies and complementarities between innovative product and process technologies, such as the ones proposed by this thesis.

Technical add-ons and hybridization can also be important interactions within system innovation, suggesting that niche technologies may not necessarily have to begin by competing directly with the dominant regime technology but, rather, form a sort of symbiotic relationship. An obvious example of this sort of interaction is the gasoline-electric powertrain, which found its initial success in the early 1990s. It is also possible that the ICE will play an important role in the transition towards EM in the form of PHEVs and BEVx. These options can provide some of the sustainability benefits of a full-BEV while reducing range anxiety.

Another example is the use of both electric and gasoline powertrains in high performance vehicles. The instant torque and swift acceleration of electric motors is being leveraged to improve the driving dynamics of high-performance vehicles. Porsche's new Panamera Turbo S E-Hybrid sports sedan is a prime example of electrification being used to enhance performance rather than efficiency (Ayapana, 2017). The potential benefit of such a relationship is consumer education, promoting the unique benefits of electrified vehicles (including their performance) and providing consumers with an alternative perception of PEVs.

9.2 Has a Transition Already Begun?

The above discussion on socio-technical transitions and the MLP framework suggests that hypothesizing specific timelines or outcomes for a potential regime transition is far from straightforward and requires careful consideration of the various elements and actors—at multiple dimensions—that are involved with a particular socio-technical system and the complex, dynamic interactions that occur between them. It is therefore not the author's intention to outline a specific timeframe of events for a full-scale transition to MFR-style production and distribution in Canada or when either AM of EM will successfully breakthrough the existing regime to compete directly with the dominant technologies, potentially facilitating system innovation. There is a need however for future research on this topic using the MLP as well as a full cost benefit analysis (CBA) of the economic impacts of a potential transition to MFR-style production in Canada.

9.2.1 3D Printing Production Parts

Despite substantial uncertainty regarding the potential timeframe for system innovation, there are signs that change is underway. For instance, at least two global OEMs have publicly acknowledged the potential opportunities and benefits of AM beyond rapid prototyping. Ford announced in March of 2017 that it had begun testing Stratasys' new 3D printer for the production of large-scale, single-piece automotive parts. The company also said it would be exploring potential applications of 3D printing for use in future production vehicles, including Ford Performance parts and personalized auto parts. The increased affordability and efficiency of newer 3D printing technologies were cited as reasons for the endeavour as well as the ability to produce lightweight parts for improved fuel efficiency (Ford, 2017).

Similarly, in August 2017 Mercedes-Benz Trucks celebrated the first 3D printed spare metal part used on a production vehicle. The company said the thermostat cover passed all levels of their "stringent quality assurance process" and even boasted that the company was a "technological leader in the challenging segment of cutting-edge 3D printing processes for metal components" (Daimler, 2017). Daimler AG's heavy-duty truck division recognized the considerable flexibility and cost savings offered by 3D printing metal components for infrequently ordered spare and specialty parts for both small and classic model series. This allows the company to provide its customers with the assurance of receiving spare parts quickly at an affordable price, regardless of the age of their vehicle. The company first used the technology to produce replacement aluminum parts, which had a greater density and purity than their traditional die-cast aluminum components. The 3D printed parts were stronger, harder, and required no additional development costs or specialized tooling. Future areas of use for the technology include complex metal components for engines and peripheral parts, as well as parts in cooling systems, transmissions, axels, or chassis. Additive manufacturing of metal components allows high-strength and thermal resistant components with complex geometries to be produced cost effectively, at the touch of a button in almost any quantity (Daimler, 2017).

It should be noted that by adopting AM technologies for the purpose of manufacturing one-off and small batch replacement parts for aging vehicles, the company is adopting one of the sustainability principles of the MFR concept which encourages extending vehicle life cycles through repairing, updating, retrofitting, and remanufacturing to reduce technological obsolescence and premature vehicle scrapping. Additive manufacturing therefore provides companies with the flexibility they require to pursue sustainability initiatives that would have previously been too costly and unprofitable.

9.2.2 Electric Mobility Favoured Over Other Green Alternatives

With respect to the emergence of an EM regime, several examples have already demonstrated an increasing momentum, including the decision by some luxury brands to pursue a dedicated EV strategy as well as the recent decision by lawmakers in some jurisdictions to ban the sale of ICEVs within the next few decades. The selection of electrification over rival propulsion technologies is evident in the recent shift by certain VMs that previously championed HFCVs as the primary solution for the future of sustainable mobility to increase their investments in battery technologies. For instance, South Korea’s Hyundai Motor Company announced in August of 2017 that it was shifting the focus of its future product strategy towards greater electrification (Jin, 2017). The parent company of Hyundai and Kia updated its eco-friendly car strategy, which now includes plans for eight battery-powered vehicles and two HFCVs. The previous strategy, announced in 2014, had included only two PEVs among a planned 22 eco-friendly models (Jin, 2017).

Similarly, the Toyota Motor Company had felt that HFCVs were the superior ZEV technology, citing the restricted use of BEVs due to their limited range and long recharging time (Voelcker, 2017). Pressured by increasingly stringent emissions requirements in China, the world’s largest automotive market, Toyota announced it would begin building BEVs as early as 2020. News reports from a Japanese newspaper have also suggested that Toyota is investing heavily in battery technologies to overcome the barriers that, in its view, limit the utility of BEVs. Toyota is said to be in the process of developing a next generation solid-state battery (Voelcker, 2017). If the report is true and Toyota does launch a solid-sate BEV by 2022, it would be the first global OEM to use the technology in a production vehicle. Solid-state batteries have a reduced risk of fire from overheating and a greater energy density than lithium-ion batteries, meaning a longer driving range from smaller battery packs as well as faster re-charging (Voelcker, 2017). However, unlike lithium ion batteries, which have increasingly become less expensive, solid-state battery cells remain costly to produce, especially in high volumes. If successful, Toyota could gain a significant first-mover advantage over its competitors.

Despite being extremely difficult to predict with accuracy when AM and EM will break through the mainstream regime and compete directly with the existing production and consumption paradigm in the automotive industry, it can be argued that these technologies are being improved within their respective niche (by both incumbents and new entrants) suggesting the first phase of a socio-technical transition is well underway.

9.3 Circumstances in Canada that Favour System Innovation

The discussion section has so far focused on ways in which to analyze the dynamics of systemic change at the level of societal functions using a socio-technical approach and the MLP to examine the complex, multi-dimensional interactions that are involved in system innovation. Based on this understanding, circumstances in Canada will be examined to consider whether they favour a transition to MFR-style production and distribution, enabled by AM and EM.

9.3.1 The Changing Role of Automotive Governance in Canada

Beginning in the 1960s Canada's auto industry steadily increased its share of North American vehicle production, bringing immense benefits to the Canadian economy, until its peak in 1999. The industry accounted for significant levels of employment, trade, and contributions to national GDP (Mordue & Sweeney, 2017). Sector-specific policies and trade tools designed to grow and sustain the country's automotive manufacturing footprint helped bolster the industry's success through the second half of the 20th century. Notable growth between 1965 and 1974 was fuelled by the Auto Pact's rapid integration of the automotive industries in Canada and the US (Mordue & Sweeney, 2017). Licensed manufacturers were permitted to import finished vehicles and automotive parts into Canada tariff free, provided they satisfied production and value-added requirements designed to safeguard the Canadian industry. This encouraged Canadian assembly plants to produce a narrower range of models for sale in both countries to achieve greater production efficiency and economies of scale.

On several occasions between 1965 and 1980, the Canadian government strategically invoked these safeguards to secure additional investments from OEMs who had failed to meet the requirements (Mordue & Sweeney, 2017). In exchange for waiving retroactive tariffs linked to production and value-added shortfalls, Ford, Chrysler, and GM made commitments to increase

Canadian production. The passing of the Medical Care Act in 1966 also contributed to growth in the auto industry in the late 1960s and early 1970s by significantly reducing labour costs in Canada compared to the US by reducing employer healthcare costs (Mordue & Sweeney, 2017).

Beginning in the late 1970s however, the effectiveness of Canada's existing policy measures to expand the industry began to diminish. The aforementioned safeguards had even lost their influence as existing investments sufficiently ensured that OEMs would be in compliance well into the future (Mordue & Sweeney, 2017). The Auto Pact had also contributed to intense competition between subnational jurisdictions across North America for new investments (Anastakis, 2013). For instance, in 1976 the State of Pennsylvania offered nearly $70 million worth of incentives to VW to attract its first North American transplant. The precursory bidding war to that decision highlighted the extreme lengths both local and state governments were willing to go to entice OEMs for their investment and the political tools they were prepared to use (Anastakis, 2013).

As such, Canadian policy-makers felt compelled to establish an incentive strategy to remain competitive. In 1978, the Canadian and Ontario governments jointly provided Ford Canada with CAD $68 million to build a new engine plant in Windsor, Ontario (Mordue & Sweeney, 2017). The 1.3 million square-foot facility designed to build more than 600,000 engines annually (80% of which would be exported to the US) was Ford's single largest investment in Canada at CAD $535 million (Anastakis, 2013). The plant's estimated 2,600 employees each accounted for CAD $26,000 of the government's financial support. Opponents were upset that the government had entered into a bidding war with US states and saw the incentives as a failure by the government to compel automakers to follow through with their investment obligations (Anastasia, 2013). Despite these criticisms, the practice of subsidizing new automotive investments became increasingly commonplace and therefore necessary. From 1980 onward, nearly all greenfield assembly plants and an ever-growing number of automotive parts plants received some type of direct or indirect incentive package from the Government of Canada and Ontario (Mordue & Sweeney, 2017).

Furthermore, once Japanese owned OEMs became a competitive threat, voluntary export restraints (VERs) were used to protect the interest of US-owned OEMs in Canada. However, the tariff mechanism quickly became a tool for encouraging Japanese investments in Canada. By the end of the 1980s, both Toyota and Honda had built their first Canadian assembly plants, while Suzuki entered into a joint venture with GM for a Canadian plant (Mordue & Sweeney, 2017). Leading up to 1999, both Honda and Toyota more than doubled their production capacity in Canada by adding additional assembly lines to existing facilities. One reason for this continued growth was the joint impacts of a lower currency and subsequently lower labour costs vis-à-vis the US. Furthermore, Canadian assembly plants had gained a reputation for quality, earning a disproportionate number of J.D. Power Plant and Vehicle Quality Awards (CAPC, 2013). Unfortunately, the momentum would soon fade.

9.3.2 The Incentives Debate

Despite prolonged and uninterrupted growth throughout the second half of the 20th century, various decisions and events after 1999 began to erode Canada's competitive advantage (Mordue & Sweeney, 2017). The most impactful event was most likely the termination of the Auto Pact; within three years of its dismantling, three "domestic" OEM plants were shuttered. Somewhat mitigating the negative impacts of these closures was the decision by Toyota Motor Manufacturing Canada (TMMC) in 2005 to build a new plant in Woodstock, Ontario—the first greenfield plant that had been built in Canada within the previous two decades (Yates & Lewchuk, 2017). Helping secure this CAD $1.2 billion investment was a joint incentive package funded by the federal and provincial government valued at more than CAD $200 million.

The use of incentives to attract automotive investments in Canada was a divisive issue. There was public debate over their efficacy in terms of job creation and economic spin-offs as well as over the role of the government and the appropriateness of using public funds to subsidize investments by large, profitable multi-national corporations (Yates & Lewchuk, 2017). Opponents argued that companies should and would invest so long as it made sense economically and that the government's role was only to ensure that the cost of doing business in Canada was competitive (Yates & Lewchuk, 2017). Conversely, supporters of the incentives argued that the practice had become a necessary fact given the fierce competition with other sub-national jurisdictions eager to capitalize on the benefits of automotive investments.

Yates and Lewchuk (2017, p. s16) conducted an analysis of TMMC's decision to locate its new greenfield assembly plant in Woodstock to "explore the relative importance of government incentives in influencing automotive Corporations' decisions to invest in Canada…"

The researchers concluded that locational factors such as the cost of labour and utilities, proximity to parts suppliers, logistical infrastructure, and tax structures, are important and must be sufficiently competitive to attract investments. Although it is now rare for a VM to invest anywhere in North America without government support, the authors noted that other, non-economic "soft factors" were often the final determinants of locational decisions. These included the relationship between a corporation's headquarters and its branch plants, and the leadership demonstrated by a particular branch plant and its operations. Actor relationships were also found to affect investment decisions; particularly, the relationship between corporate actors at a company's home office and the local office where the investment is being considered, between levels of government, and between political actors and automotive managers (Yates & Lewchuck, 2017). The research suggested that investment decisions were both an economic and social process.

The Woodstock plant benefitted immensely from the participation of TMMC's then president and CEO Ray Tanguay, who held a prominent position within Toyota's global management hierarchy. Moreover, as a Canadian, Tanguay's enthusiasm and passion for Canada was transferred directly to Toyota's Japanese headquarters (Yates & Luwchuk, 2017). The uniquely Canadian proposal that was presented to Japanese decision makers involved choosing a location that was accessible to Toyota's existing Cambridge, Ont. plant to leverage the experience and skills of that facility along with its robust supplier network. Tanguay had created a reputation for the Cambridge plant, which had become a benchmark for quality and productivity among Toyota's other plants. The research showed that Tanguay's personal reputation and his relationship with the corporate headquarters was critical in securing the Woodstock investment. Several other interviews conducted for the research confirmed the importance of a strong local champion within an OEM's corporate structure to secure investments.

Investing in an automotive assembly plant is a long-term, often multi-million dollar proposition that involves considerable risk as a result of incomplete information regarding future costs and long-term profitability. While government incentives are an important (and even necessary) part in offsetting these costs and reducing potential risks, it is often the lack of precise information regarding future costs that makes non-economic soft factors so pivotal for investment decisions (Yates & Lewchuk, 2017). In the absence of complete information, popular perceptions of a location's attractiveness can influence investment decisions. The research therefore suggested that governments help shape these perceptions to improve a location's relative attractiveness in addition to incentives that are clear and uniform across all levels of government and designed with the interests of the investor in mind. Within the context of the TMMC plant in Woodstock, the research revealed that in general, Canada was perceived as "a high-cost location with a difficult labour environment and a government that can be indifferent to the needs of investors" (Yates & Lewchuk, 2017, p. s26). Characteristics such as the quality of Canadian labour, the stability of Canadian society, and Canada's favourable tax regime were also mentioned but were understated in comparison.

The researchers concluded that governments in Canada must be tasked with creating a strong value proposition for investing in the country and ensuring that this value proposition is emphasized and articulated within the popular perceptions that exist about Canada. A potential disadvantage is the lack of domestically owned OEMs, which means investment decisions often rely on foreign senior managers. Yates & Lewchuk (2017) advocated that a stronger emphasis be placed on promoting a strong value proposition that effectively communicates locational advantages; cultivating trustworthy and respectful relationships between government officials and senior managers; and using a single unifying framework between levels of government to coordinate and support potential investments.

9.3.3 The Reality of Incentives and Automotive Investments in Canada

Despite the public debate over the TMMC plant, the practice of offering incentives to attract investments has occurred since the 1970s. A far more controversial decision according to Mordue & Sweeney (2017) was to incentivize OEMs for merely maintaining or modernizing their existing operations. For instance, Canada and Ontario jointly provided Ford Canada with incentives valued at CAD $200 million for an investment at its Oakville assembly plant, despite a decision by Ford to discontinue production at another plant on the same site. Both governments once again provided incentives to GM (valued at CAD $400 million) for investments made to four of its Canadian assembly plants and to DaimlerChrysler (valued at CAD $122.8 million) for an assembly plant and an R&D facility (Van Biesebroeck, 2010). Throughout 2005 and 2006 a number of suppliers (both foreign and domestic) also received incentives valued between CAD $6 million and $62 million.

This shift in public policy however, was not enough to reverse the industry's steady decline between 2000 and 2007, before the financial crisis sent the industry into freefall. Canadian vehicle production fell 42% between 2007 and 2009 from 2.58 million units to 1.48 million units (Mordue & Sweeney, 2017). The industry recovered modestly after 2010 and production stabilized around 2.3 million units in 2012. The recovery in the US and Mexico however was much more pronounced than in Canada. Several large greenfield investments in the Southern US and in Mexico were announced over the same period that Canadian vehicle production had declined. In Canada, not a single greenfield assembly plant has been built since the TMMC plant ended construction in 2008.

Particularly concerning in the Canadian context according to Mordue and Sweeney (2017) is the lack of investment into additional production capacity. Most VM operating in Canada have made at least one investment since 2011 to update an existing facility (e.g., retooling a production line) but at a significant cost to taxpayers. Toyota, Honda, Ford, and FCA have collectively received incentives valued at CAD $590 million between 2011 and 2016 to renew production mandates at existing facilities. On average, the incentives represented 16% of the total costs of retooling a production line. General Motors did not receive incentives during this period due to the financial support it received in 2009 in exchange for maintaining a portion of its North American production in Canada until 2016. The financial bailouts of GM and Chrysler mandated that concessions be made in all collective bargaining agreements in Canada and the US to ensure labour costs were competitive with non-unionized workforces. The bargaining power of unionized workers was drastically reduced in the aftermath of the financial crisis, as a work stoppage at the time was inconceivable. Unionized autoworkers were forced to focus their bargaining efforts on renewing production mandates rather than on gaining new greenfield investments or increasing workers’ wages and benefits (Mordue & Sweeney, 2017).

Mordue and Sweeney (2017) contended that the competitive advantage that high quality work forces in regions like Canada once had has been eroded in a process the authors refer to as the commoditization of automotive labour. The researchers cited several conditions that have contributed to this phenomenon (p. 183):

1) "The relative ubiquity of quality;

2) Standardization and replicable manufacturing production systems and capitalization;

3) OEMs' ability to recruit and retain workers from the top tiers of the labour market regardless of location; and

4) The growth of luxury vehicle production in the US South and Mexico".

The fact that Mexico's share of North American vehicle production has rapidly increased during the same period that Canada's share has diminished suggests that quality alone is no longer an effective means of attracting new investments (Mordue & Sweeney, 2017).

The diffusion of standardized production systems with identical methods and equipment has been used to minimize discrepancies in productivity and quality across facilities, essentially eliminating locational differences (Mordue & Sweeney, 2017). The spread of the TPS and later the adoption of lean production methods by most other manufacturers reduced intra- and inter-firm productivity differences. As such, automotive labour has become an increasingly homogenous commodity. The proliferation of technology and automation has also accelerated the commoditization of labour. Canadian and Mexican automotive workers not only use an equivalent manufacturing process but are also now doing so with comparable levels of automation. The technological gap between Canada and Mexico is quickly diminishing as the latter has rapidly increased its levels of automation while the former has remained steady for nearly a decade (Mordue & Sweeney, 2017).

Differences in average education have even become less relevant. The industry has historically relied on competitive wages and benefit packages to attract and retain a skilled workforce. As such, OEMs have been able to recruit workers from the top tiers of the labour market, rendering differences in education indistinguishable between Canada and Mexico for instance. Canada has previously reasoned that its "well-educated workforce, established supply base, and reputation for quality" could be leveraged to attract automotive investments from premium brands, which often benefit from higher margins (Mordue & Sweeney, 2017, p. 184). However, this strategic narrative proved unsuccessful in 2015 when Canada failed to woo investments from Jaguar-Land Rover, and Volvo. Comparatively, premium German brands

BMW, Audi, and Mercedes-Benz, and Nissan's premium Infiniti brand have all begun constructing assembly plants in Mexico with a combined annual production capacity of over half a million units (Mordue & Sweeney, 2017).

The joint impacts of increased competition, increased dependence on incentives, and the commoditization of automotive labour in North America have eroded much of Canada's competitive profile and increasingly challenged policy makers and labour unions in Canada, which have been unable to grow the industry over the last two decades and instead have been forced to adopt policies and negotiating strategies that focus merely on maintaining what capacity still exists. The most recent round of collective bargaining by the Canadian automotive labour union Unifor confirmed that the consolidated line (one of two GM plants in Oshawa, Ont., which currently builds the Chevy Equinox) will be shuttered in 2017 as production shifts to GM's CAMI plant in Ingersoll, Ont. (Owram, 2016). The flex line (the second Oshawa plant which currently produces the Buick Regal, Chevy Impala, and Cadillac XTS) has also faced significant uncertainty over its future since production of the Chevy Camaro was shifted to Michigan and given that a production mandate for the plant has not been confirmed beyond 2019 (Lu, 2016). Given that GM's commitments to the Canadian Government (following its 2009 bailout) to maintain minimum production levels in Canada expired in 2016, there was significant uncertainty over GM's future footprint in Canada, and in Oshawa specifically.

Unifor had also been concerned about the future of Ford's Essex engine plant in Windsor, which lost out in a bid to produce certain next-generation engines to a facility in Mexico, and FCA's Brampton assembly plant that will require upgrades to its paint shop in order to continue production (Owram, 2016). In March of 2017, Ford announced alongside the Premiere of Ontario and the Prime Minister of Canada that the three parties would be jointly investing in a new engine program for the Essex plant and for a new research and engineering centre in Ottawa that will focus on infotainment systems, driver-assist features, and autonomous vehicle technology (CBC, 2017b). Additionally, Unifor successfully bargained with FCA for a new paint shop in Brampton. This does not necessarily secure the plant's future, but is a step in the right direction towards achieving a future production mandate.

Despite such favourable announcements, Canada still appears unable to expand its manufacturing footprint or effectively compete with other jurisdictions for new investments.

Such circumstances leave much uncertainty over Canada's future competitiveness and its future share of North American vehicle production given the favourable circumstances that exist in both Mexico and the Southern US. The most recent greenfield investment announced for North America is a new $1.6 million joint venture between Japanese automakers Mazda and Toyota set to open in 2021 somewhere in the US (CBC, 2017a). The facility will have an annual production capacity of 300,000 units and employ an estimated 4,000 workers. Toyota announced it would build the next generation Corolla compact sedan in the new plant whereas Mazda plans to build crossover vehicles. The Corolla, which is currently assembled in Cambridge, Ont. and a plant in Mississippi, was set to be relocated to a new facility under construction in Mexico prior to this announcement. The Ontario government has given Toyota $41 million, along with $59 million in repayable loans from the federal government, to retool assembly lines in Toyota's Cambridge and Woodstock plants to produce of the RAV4 crossover (CBC, 2017a). Once again, Canada is being overlooked for new investments while taxpayers are subsidizing the continuation of production mandates in Ontario's existing assembly plants.

9.4 Potential Short-Term Opportunities for Canada's Auto Industry

Based on the discussion of socio-technical systems and transitions, it should be evident that change occurs gradually, often over several decades, and relies on the complex interplay between various elements and stakeholders. As such, this thesis attempted to propose a set of innovative technologies that could facilitate system innovation in the automotive industry, resulting in greater long-term sustainability in the form of MFR. However, before a full-scale transition towards MFR can occur in Canada, or anywhere, there must be a series of intermediate changes to either prop-up emerging niche technologies or put pressure on the existing regime. Therefore, it is useful to discuss possible short-term opportunities that a transition towards greater sustainability could create for Canada's automotive industry.

One such opportunity could be to transition the focus of growing Canada's auto industry through its traditional role in vehicle manufacturing towards one that is based in innovation and invention, allowing future investments in manufacturing activities to occur in other, lower cost jurisdictions. A 2016 report by the Canadian Automotive Partnership Council (CAPC) stated that: "rapid advancements in technology, changes in consumer preferences and new entrants into the global auto sector are inspiring new automotive products, services and business models that will be increasingly electric, digitally connected, autonomous and part of the sharing economy" (p. 1).

Despite the fervent pace and scope of technological development in the automotive industry, the CAPC argues that such transformations and changes represent a potential opportunity for Canada to shift its position within North America's automotive sector. The intention of the CAPC report was to offer recommendations and guidance to the Canadian Government for its strategy on innovation, which it hopes will foster economic growth. The position taken in the report is that in light of various global manufacturing headwinds, including increased global competition, shifting patterns of global trade and free-trade agreements, and a range of policy and macroeconomic factors, the only pathway towards future growth in Canada's automotive industry is one of innovation.

The industry's legacy of focusing exclusively on manufacturing competitiveness rather than on selling Canada as an attractive location for invention, R&D, and engineering activities has been reflected in differing OEM mandates and the varying proximity of OEM facilities in Canada to their engineering headquarters. There are some signs, however, that perceptions of Canada's role in the automotive industry are changing. In 2016, GM located 1,000 engineering and R&D positions in Canada in the areas of autonomous vehicle software & controls development, active safety and vehicle dynamics technology, and infotainment and connected vehicle technology, which could suggest that OEMs may be reconsidering their views on Canada's automotive ecosystem and its potential to serve as a location for overflow innovation activities in conjunction with academic and research institutions and emerging technology start-ups (CAPC, 2016). For this trend to continue and for Canada to generate new pathways for high value economic growth, higher paid employment, and opportunities for Canadian companies to scale up their activities and global competitiveness, the Government of Canada must develop an "integrated auto innovation strategy" (CAPC, 2016).

To be effective in this regard, the CAPC suggests that Canada's auto industry must have access to talent, customers, capital, and must be supported by a welcoming regulatory and intellectual property environment. Talent is the foundation of Canada's future innovation economy. Given the concentration of Canada's automotive industry in Ontario, the province is well positioned to supply the necessary talent to both incumbent and entrepreneurial firms given its base of students educated in science, technology, engineering, and mathematics and its world-class institutions specializing in such emerging fields as software development and artificial intelligence (CAPC, 2016). Despite these qualities, the province has struggled with maintaining this talent and with aligning its research institutions with the dynamic needs of specific industries. There is a need for greater strategic coordination between academic institutions and the needs of specific growth industries like the automotive sector.

The economic value of innovation is derived from customer interest and willingness to pay. The innovation process must therefore be dynamic and consumer focused. The Canadian automobile sector must harness its connectedness with global automotive supply chains to ensure that a strong value proposition for Canada's auto industry is effectively communicated to the decision makers of global VMs. It is essential that such supply-consumer relationships be cultivated if Canada is to commercialize its knowledge assets through innovation and invention (CAPC, 2016).

The importance of capital and financial incentives in developing (and then maintaining) Canada's automotive manufacturing footprint was discussed. Such financial tools can also play a vital role in developing "innovation ecosystems" (CAPC, 2016). Government incentives for innovation must effectively support the various stages of commercialization and accounts for the dynamic and nonlinear process that innovation often follows. There are also distinct differences between the process of innovation of new entrants and start-ups vs. larger incumbents, and the type of support they require, which should be accounted for when allocating incentives.

The final ingredient of a successful auto innovation strategy is an inviting regulatory environment for innovation activities that are associated with high value economic growth. It should be noted that just as government policy and regulation could be used to spur innovation and economic growth, it can equally stifle innovation as it plays an important role in the locational decisions of OEMs, including for R&D activities. Governments in Canada must develop strategies that target the sector specific needs of the auto industry vis-à-vis innovation (CAPC, 2016). Governments should also create a favourable market for patents and intellectual property rights as to facilitate the protection and sale of ideas. This will become increasingly important as more technology companies enter into the automotive ecosystem, creating an opportunity for high value growth and employment.

The recommendations contained in the CAPC report appear to be relevant in terms of creating valuable intermediate opportunities for Canada's automotive industry as it grapples with a transition towards greater sustainability and perhaps, MFR over the longer term. Specifically, the existing network of OEM facilities and automotive suppliers that already exist in Ontario should be leveraged as much as possible, suggesting Ontario is likely to lead in the transition of Canada's automotive sector. An analysis of patent data across a period of 35 years demonstrated that despite a decline in manufacturing activities, the Detroit auto cluster has increased its innovation activities as a result of sustained local knowledge (Hannigan, Cano-Kollmann, & Mudambi, 2015). The authors contended, "The very forces that bring about the decline in manufacturing activities in a cluster sustain their position as a global centre of innovation excellence" (Hannigan et al., 2015, p. 613). These findings suggest that a decline in manufacturing activities does not necessarily spell the end of an industrial cluster but rather a shift to a new stage, focused on more knowledge based activities such as R&D and design.

Regionalization in the global automotive industry and increased North American competition for new investments suggest that Canada may be unable to sustain its current manufacturing footprint. However, perhaps some important parallels can be made between the connected automotive clusters in Detroit and Southern Ontario in order for the industry in Canada to shift towards more knowledge based activities, at least in the near-term, as the industry undergoes a sustainability transition. In the case of plant closures, R&D activities, which often require a smaller, but more specialized and skilled workforce, would be unlikely to fully replace all of the resulting job losses. However, such activities could be critical in offsetting some of the economic losses associated with plant closures with high value and skilled employment. In the context of this thesis, it is suggested that R&D activities related to EM and AM be prioritized as well as exploratory initiatives related to innovative business models in order to ensure the longer-term goal of facilitating a transition towards MFR. Because Canada is at a disadvantage as it often relies on foreign decision makers to allocate investments, policy suggestions such as those made by Yates and Lewchuk (2017) should be heeded by all levels of government to increase Canada's overall attractiveness and to develop a clear value proposition for R&D and innovation activities in Canada.

Canada's highly skilled labour market could be leveraged to transition towards more R&D activities to coincide with major industry trends like electrification, autonomous or self-driving vehicle technologies, and vehicle connectivity. Canada is becoming a cradle for artificial intelligence (AI) research with major tech-companies like Google and Microsoft investing in AI research in partnership with Canadian Universities and increasing their Canadian workforces (Darrow, 2017). In order to support such a transition and ensure that Canadians are equipped with the skills necessary to support innovation in the automotive sector, governments in Canada must invest in skills development, research, and partnerships between academic institutions and industry. The federal government included CAD $125 million in its most recent budget for a Pan-Canadian Artificial Intelligence Strategy as part of its effort to support digital innovation in Canada (Shecter, 2017). Further evidence of Canada's skilled labour force and its ability to support R&D activities is the inclusion of the University of Toronto and Waterloo among six North American institutions in a three-year long competition to develop a self-driving Chevy Bolt EV hosted by GM and engineering association SAE International (Casey, 2017).

Another potential short-term opportunity for Canadian part suppliers, specifically for larger, integrated Tier 1 suppliers is to increase their capabilities in electrification and battery technology and become contract manufacturers for OEMs looking for expertise in the area and struggling to develop their own PEV strategy in line with changing consumer demands and regulatory requirements. For instance, by 2018 Canadian owned Magna will be manufacturing five different models around the world for global OEMs including two PEVs: the Jaguar I-PACE and the BMW 530e plug-in hybrid (Magna, 2017). Despite none of these vehicles being manufactured in Canada, it alludes to potential opportunities and suggests that governments and unions in Canada should be supportive of large Tier 1 suppliers who could, in the future, play a greater role in vehicle manufacturing and/or R&D. Canadian suppliers with expertise in electrification and manufacturing, for instance, could expand their operations to include the manufacturing of EVs on a contract basis for OEMs with less expertise in electrification and battery technology.

9.5 Potential Long-Term Implications of Micro-Factory Retailing in Canada

Short-term opportunities for Canada's automotive industry towards higher value activities including, innovation, R&D, design, and engineering were proposed as an intermediary step within a much larger sustainability transition involving changes to how cars are manufactured, distributed, and operated. The MFR concept represents a potential alternative for the future. Assuming such a transition is successful in Canada, what potential outcomes are to be expected? Once again, system innovation is a gradual process, which makes predicting potential outcomes of a particular transition rather challenging. However, assuming there was a more rapid transition to MFR in Canada, what fundamental changes could be expected? The current regime relies primarily on the sale of new vehicles produced in large-scale, capital-intensive and centralized facilities designed to achieve large economies of scale. Alternatively, MFR production is much less capital-intensive, which creates fewer barriers to entry and thanks to lower volumes and an emphasis on economies of scope rather than scale it is also more adaptable. Distributed micro-factories combining both manufacturing and retailing activities facilitate the use of new and sustainable business models like PSS, which involve VMs in more downstream activities in the value chain.

First and foremost, transitioning from a centralized to a distributed manufacturing model would likely have significant impacts on the geography of automotive production in Canada, which is currently concentrated in Ontario. Second, Canada’s auto industry is not only highly integrated with that of the US, but is also dependent upon vehicle exports to the much larger US vehicle market. This high degree of connectedness was evident in the aftermath of the financial crisis, which resulted in dramatically reduced Canadian automobile production. As such, it can be assumed that a shift towards more localized auto manufacturing in North America, along the lines of MFR, would likely result in a net loss of employment and production capacity in Canada. Employment losses would not only be restricted to vehicle and parts manufacturing, but would include retailing and repair/maintenance jobs as well. Car dealerships and repair shops would likely become obsolete in a transition to MFR. It could be argued however that the role of car dealerships in the current system is already under threat because of industry trends like electrification (PEVs require far less maintenance—a significant source of revenue for car dealerships), reduced car ownership (as a result of the increased popularity of mobility-services), and direct or online vehicle sales (a model used by Tesla Motors).

9.5.1 The End of Franchised Car Dealerships

A controversial report published by the independent think tank RethinkX forecasted the speed and scale of technology-driven disruption in the transportation sector (Arbib & Seba, 2017). The authors, perhaps optimistically, predicted the rapid diffusion of new mobility business models, which they called "transportation-as-a-service" (TaaS), and suggested that up to 95% of US passenger miles would be replaced by on-demand autonomous EVs (owned by fleets rather than individuals) as early as 2030. The difference between their findings and that of other similar studies is the pace of technological disruption. As opposed to assuming technological disruption will occur linearly and incrementally, the authors incorporated system dynamics (e.g., feedback loops, network effects, and market forces) within their models that allow technological adoption to occur exponentially along an S-shaped curve (similar to the one proposed by Rogers diffusion of innovation theory) that will create a cycle of decreasing costs and increasing quality of service and convenience. The researchers predict that the widespread adoption of TaaS would dramatically reduce new vehicle demand in the US, resulting in 70% drop in annual vehicle production by 2030.

Among their predictions is that new vehicle sales for individual ownership would end as early as 2024, which would spell the end of franchised car dealerships. As for VMs, they will be forced to either become low-margin, high-volume assemblers of autonomous EVs or providers of TaaS. Future value in the industry, they suggest, will mainly be created by vehicle operating systems, computing platforms, and TaaS platforms. This report suggested that if the adoption of EVs occurs exponentially, a large-scale transition with many significant economic impacts could occur much sooner than many industry analysts, policy makers, and consumers are anticipating. Even if the actual timeline presented in this report proves to be overly optimistic, it does provide some evidence of potential future outcomes for the automotive industry. Furthermore, there are many similarities between full-scale PSS providers of EM, as presented in this thesis, and the TaaS concept presents in the RethinkX report. The major difference between the two concepts is that RethinkX anticipates the continuation of high-volume auto manufacturing as opposed to small-scale MFR-style production proposed by this thesis. This difference could be the result of Arbib and Seba's (2017) assumption that individual ownership will cease to exist before 2030 suggesting that flexible and customizable vehicle production is less relevant to fleet operators providing TaaS.

9.5.2 Pronounced Changes in the Province of Ontario

As far as Canada is concerned, due to the high concentration of automotive assembly plants and parts suppliers in Ontario, it is likely that the most noticeable and significant changes would be felt in Ontario assuming a transition to MFR. However, as previously discussed, this concentration of knowledge would also provide Ontario with many distinct opportunities throughout the transition process, assuming it occurs more gradually than what Arbib and Seba (2017) have predicted. Alternatively, the other provinces across the country that have traditionally been excluded from the automotive industry in Canada would likely experience a net economic benefit due to the spatial distribution of manufacturing activities in the MFR concept. Urban centres with high populations would likely be the first to attract a small-scale manufacturing facility to satisfy local and regional demand. A unique consideration for MFR in Canada is the country's large land mass and distributed population. Unique solutions and business models would likely have to be developed in the Canadian context for areas with insufficient demand to support a local micro-factory.

One possible solution or adaptation to the MFR model that could be the used to overcome this problem is the use of small design studios or storefronts (similar to Tesla’s retail strategy) that customers could visit to customize a made-to-order 3D printed PEV. The personalized 3D digital model of their vehicle could then be sent to a regionally located micro-factory to be manufactured. Finished vehicles would then have to be transported short distances to be delivered to customers. Online design studios and configurators could also feasibly replace the need for brick-and-mortar stores or retail locations. Furthermore, Tesla’s current model for vehicle repair and maintenance could be appropriate in Canada in the context of MFR. Tesla uses a combination of physical locations and mobile service appointments to look after its fleet of vehicles (Lambert, 2017). Thanks to fewer moving parts and lubricants to keep them moving, PEVs require less maintenance than ICEVs. Furthermore, as vehicles become increasingly connected, issues can be diagnosed remotely and either resolved via over-the-air software updates or a mobile service appointment at a customer’s home or workplace.

Given the current structure of the Canadian automotive industry and its reliance on US automotive demand, it is likely that a shift to MFR would create a net loss in automotive manufacturing jobs as Ontario’s large assembly and parts plants are shuttered in favour of small-scale 3D printing enabled micro-factories distributed across the country to satisfy domestic demand. Despite the economic losses from fewer manufacturing, dealership, and maintenance/ repair jobs, the MFR concept has the potential to create entirely new revenue opportunities for Canadian companies that are successful in innovating their business model and the consumer interface to participate in more downstream value-added activities. Even with the distributed nature of the MFR concept, it is suggested that some common elements like batteries, for instance, will continue to be mass-produced in centralized facilities to reduce costs through economies of scale. Canada could use its vast knowledge base to pioneer developments in advanced battery technologies and become a major supplier of EV batteries. Similarly, Canadian companies could develop new AM technologies and systems specifically for the automotive industry and become a global supplier of 3D printers to enable micro-factory production. The above suggestions are educated hypotheses that should be explored in more detail as part of future research regarding a sustainable transition in Canada's automotive industry and the potential economic outcomes of such changes.

Chapter 10 Conclusion

Using IE and the MFR concept as a basis, the primary aim of this thesis was to propose a set of innovative technologies that could potentially facilitate a transition towards a more sustainable system of automobility in Canada. Specifically, alternative process and product technologies that could feasibly replace the existing set of technologies that have dominated automobile manufacturing over the past century. This thesis attempted to explore the joint impacts of additive manufacturing (AM) and electric mobility (EM) in enabling a transition to a more sustainable form of automotive production and distribution (as suggested by MFR) and whether the circumstances in Canada are favourable to facilitate such as transition.

10.1 Overview of Thesis Contents

This thesis began by describing the dominant consumption and production paradigm that characterizes contemporary automobile manufacturing and described a more complete historical narrative for the selection of the mass production trajectory, with particular emphasis being placed on the co-evolution of product and process technologies as described by Nieuwenhuis and Wells (2007): Edward Budd's all-steel unibody and Henry Ford's continuous-flow assembly line. The previous paradigmatic shift from Craft Production to Fordism (which according to Nieuwenhuis and Wells (2007) should more accurately be referred to as "Budd-ism" to reflect the contributions of Budd's all-steel body in making high production volumes possible and facilitating automation in the automotive industry) provided context for the potentially large-scale socio-technical transition that appears to be looming over the contemporary global automotive industry. The industry's prevailing economic structure and its dominant product and process technologies are increasingly being threatened by strengthening political, regulatory, and market pressures that have emerged out of concern for the industry's lack of long-term environmental and economic sustainability. Economic processes (i.e., lock-in and path-dependence) have helped maintain the existing socio-technical regime and favoured incremental improvements in vehicle efficiency rather than radical changes through system innovation to create a new, ecologically modern, and sustainable socio-technical regime.

The second chapter reviewed contemporary attempts at regulating the environmental impacts of the car and large-scale market trends that together are providing the impetus for a potential transition towards more sustainable, low-carbon automobility. The incremental strategies pursued by incumbent VMs to adjust to these trends and challenges has proven insufficient at providing the sustainability improvements necessary to meet tightening environmental regulations aimed at mitigating the effects of transport on climate change and addressing the human health concerns associated with transport related air pollution.

Chapter Three reviewed the emerging scientific field of industrial ecology (IE) which relies on ecological metaphor and biological analogy to improve the sustainability of industrial systems. The principles of IE were applied in Chapter Four to provide a theoretical foundation for a potential alternative model for the automotive industry with regards to the manufacturing, distribution, and use of cars. The potential alternative was originally articulated by Dr. Peter Wells and Dr. Paul Nieuwenhuis (1999/2000) as a theoretical business concept based in distributed and decentralized economic theory known as "micro-factory retailing" (or MFR). At the time, there was no direct empirical evidence to support the innovative business model as it did not appear anywhere in the world. The concept was developed by envisioning what a more sustainable automotive industry could look like if innovations in product, process, and structure were used to break away from the conventional "fire and forget" business model of most global VMs, reliant on high demand and manufacturing economies of scale (Wells & Nieuwenhuis, 2017). Micro-factory retailing reimagined the manner in which cars are built, sold, and used in an idealized future of sustainable automobility by taking inspiration from existing niche car manufacturers and the sustainability benefits of localization. The concept evolved over time, gradually incorporating new elements into its vision as they developed (Wells & Nieuwenhuis, 2017).

As a means of achieving the goal of this thesis, Chapter Five explored the potential sustainability advantages of AM and its potential synergies with PEVs and MFR. Building on this, Chapter Six reviewed the growing body of research on EM, which considered the barriers to increasing PEV adoption and favourable policy devices to encourage adoption. Chapter Seven then explored the potential role of EM, alongside sustainable business models in the form of product-service systems (PSS), in a future sustainable automotive ecosystem. Micro-factory retailing is described as an ideal consumer interface for the provision of PSS based EM. To the extent that both AM and EM currently exist within the dominant paradigm, this thesis argues that the co-evolution of these technologies alongside business model innovation through the use of

PSS could facilitate a transition towards greater sustainability in the automotive industry and, in time, decentralized small-scale manufacturing in the form of MFR.

It is the contention of this thesis that if the potential synergies between AM, EM, and PSS are adequately understood and leveraged alongside one another as they develop, the industry could feasibly have the necessary tools to transition towards a more sustainable consumption and production paradigm as described by MFR. However, as noted in the chapter on IE, humans, unlike natural systems, possess the foresight to anticipate and plan for changes that occurs in response to external pressures. This foresight should be used to ensure the co-development of the proposed innovations and business models and to devise appropriate policies to support system innovation in the form of MFR.

Three innovative technology companies (KOR Ecologic, Local Motors, and Divergent 3D) attempting to disrupt the current automotive paradigm with either AM, EM, or both were studied in Chapter Eight and used to demonstrate the potential feasibility of the proposed technologies and their compatibility with the MFR concept. Although all three companies exist at the niche level and have yet to commercialize the specific vehicle's that were described, they are strong indicators of the future direction the automotive industry could take on its way towards sustainability. A significant result that emerged from the case studies was the similarity between the business models put forth by these innovative mobility companies and the MFR concept. The ideas that were being championed by these new entrants were highly compatible with the principles of MFR, suggesting a future automotive ecosystem based on MFR is indeed a very real possibility.

The discussion in Chapter Nine focused primarily on answering the broader question of how soon large-scale system innovation might occur in the automotive industry and whether circumstances in Canada favour the current paradigm or a theoretical transition to MFR. A socio-technical approach to this transition was presented as a possible means of addressing possible timelines for implementation. It was suggested that a full-scale transition to MFR would likely occur gradually, potentially transitioning through various intermediate stages throughout the process of system innovation. The Canadian context was then discussed with emphasis being placed on the lack of political and regulatory tools that remain for policy makers in Canada to grow the industry because of increased competition and the commoditization of automotive labour, which have eroded Canada's traditional competitive advantages in the automotive sector. As such, intermediary opportunities for the Canadian auto industry were discussed as well as some hypothetical implications of system innovation and MFR in Canada.

10.2 Policy Implications of the Research

The principle policy recommendation that can be derived from this research relates to the importance of developing a comprehensive government strategy that supports eco-efficient innovations in the automotive industry. Investments should therefore be focused on the development, demonstration, and commercialization of emerging technologies (such as AM and EM) and entrepreneurial firms with novel ideas and technologies looking to participate in the automotive value chain. Competitive advantage in the automotive industry will most certainly stem from innovation in the future, and as such, Canada must ensure that it creates an appropriate policy environment to support innovation at the level of both products and business models. Canada's automotive investments should not be focused exclusively on manufacturing capacity but also on supporting Canadian-owned suppliers with relevant skills and expertise in emerging technologies to support industry wide trends such as electrification, autonomy, and connectivity. The circumstances surrounding Canada's automotive sector that were reviewed in this thesis revealed that policy measures used to grow the auto industry in the past are no longer available to decision makers, while the Government's current investment strategy appears unable to attract new investments to grow the industry. Instead, investments have been focused on merely maintaining Canada's existing manufacturing footprint. Canada must therefore improve its policy environment or risk being continuously outcompeted by rival jurisdiction, namely the southern US and Mexico. This thesis has provided a potential alternative future for Canada's automotive industry and has detailed two emerging technological innovations that could be used to facilitate such a transition. However, government are a crucial stakeholder in this potential large-scale socio-technical transition and must ensure that their policies apply appropriate pressures at the landscape level of the MLP to help facilitate a sustainable transition.

A contributing factor to Canada's poor competitiveness in the North American auto sector is the fact that it lags behind both the US—and increasingly Mexico—with respect to the coordinating multi-government initiatives in its industrial policy (Yates, 2015). Research by the Automotive Policy Research Centre (APRC) suggested that "Canadian governments have tended to rely on discrete policies and actions in support of individual automotive company plans" (p. 9) rather than developing an active and coordinated policy framework for the auto industry to facilitate a "one-stop-shopping" environment for potential investors. Despite the federal government's *Automotive Innovation Fund* and the *Ontario Jobs and Prosperity Fund*, both of which have resulted in important automotive investments in Canada's auto sector, Yates (2015) noted that individually articulated policies and programs "often flounder on lack of coordination across governments or departmental ministries" (p. 9). For instance, Canadian municipalities are often brought to the negotiating table far too late in the decision making process as compared to their US counterparts, which are often directly involved in coordinating actions to attract new automotive investments in addition to offering direct financial incentives (Yates, 2015). The report noted that Canada is aware of the impacts stemming from its lack of inter-governmental coordination with respect to potential investments. The report also emphasized that Canada must work to overcome the apparent lead that rival jurisdictions have in this respect to ensure its competitiveness and the effectiveness of its industrial policy. The report suggested that if Canada is to secure a competitive advantage in manufacturing with respect to emerging technologies it must adopt a coherent and responsive innovation strategy that facilitates coordination between private firms, research institutions, and governments (Yates, 2015).

The Canadian government should also be involved in funding pilot projects and initiatives aimed at demonstrating Canadian expertise in emerging technologies and demonstrating innovative ideas in practice. In essence, each of the innovative vehicle concepts profiled in this thesis were based on functional demonstrations of innovative technologies (i.e., AM and EM) and novel ideas and aspirations (i.e., dematerialization, local manufacturing, co-creation, etc.). A successful demonstration project that could be used as a model for the future for other emerging technologies is the *Connected Technology Vehicle Showcase* (or the Connected Car Project) that was developed by the Automotive Parts Manufacturers Association with support from TMMC. The goal of the project was to promote Canadian-made technologies to global VMs to encourage their commercialization and boost employment in Canada's automotive supply sector (Munim and Yates, 2014).

Despite the fact that many of the technologies and business model innovations presented in this thesis could be classified as being either "radical" or "disruptive" in nature, the most relevant policy initiatives to accelerate their development and commercialization are not overtly complex and could feasibly be implemented by a responsive government. However, it is important to note that the automotive industry is a globally competitive industry and Canada could fail to secure a competitive advantage if it does not act quickly enough. A new report by Clear Energy Canada (2017), for instance, suggested that Canada is trailing behind it competitors with respect to EV policy and adoption and said that Canada must "speed-up and get serious" when it comes to developing a national strategic policy response for EV adoption. The report did acknowledge that the federal government's forthcoming *Zero-Emission Vehicle Strategy* could help to fill this policy gap. However, the report noted that Canada is one of only two G7 nations without a national EV incentive program and that Québec is currently the only province with a strategy to improve the availability and accessibility of EVs. Such policies are becoming increasingly important given that the waitlist to purchase a Chevy Bolt in Canada is 8 months with many dealerships having no EV in their inventory for test drives by interested consumers (Sommerfeld, 2017). A 2015 study by Canadian EV-fleet software company *fleetcarma* demonstrated the relative difficulty of purchasing an EV in Canada as compared with the US, which was found to be as much as five times more difficult in some instances (Schaal, 2016). Examples such as these suggest Canada can indeed improve its strategic response towards eco-efficient innovations and emerging automotive technologies if it is serious about competing for future automotive investments.

10.3 The Likelihood of Micro-Factory Retailing in Canada

Canada's automotive manufacturing sector is clustered in the province of Ontario and participates in highly integrated supply network that connects the region with the automotive manufacturing cluster in the US Northeast. Ontario's high degree of connectedness with the US industry is a competitive advantage along with its own network of suppliers, but is also likely to act as a barrier to large scale system innovation that would infringe on these complex supply chains. The integration between the US and Canadian auto industries does not stop there, a significant majority of the vehicles assembled in Canada are exported to the much larger US consumer market. Likewise, Canada imports a significant number of vehicles from the US and abroad. A transition to MFR would essentially require a reversal of Canada's highly integrated supply network and would also jeopardize Canada's lucrative automotive export business with the US. The immediate economic and social ramifications of these changes would simply be too great and would likely not receive the significant level of government support that would be required to facilitate a full scale transition to MFR in Canada. Any potential for significant employment losses in Ontario's auto industry would likely receive strong resistance from all levels of government as well as automotive unions, which hold a relatively powerful position in Canadian politics.

It is a useful exercise to contrast the circumstances in Canada with those of the Australian automotive sector, which has completely withdrawn its activities from the country. Micro-factory retailing would therefore be a far more compelling alternative in the Australian context given that it has already experienced the loss of its automotive industry, and the significant economic and social benefits it provided. Micro-factory retailing therefore represents the prospect of returning some of these benefits to the country even if it is to a lesser degree than before. There is a much greater window of opportunity in Australia and foreseeably greater political support for radical innovations such as MFR. Although Canada has been unsuccessful in growing its automotive industry over the last two decades, the automotive industry in Ontario still supports significant economic benefits for both the province and the country. Canada is much less isolated than Australia and benefits tremendously from its close proximity to the second largest automotive market in the world. Such factors make a full transition to MFR comparatively less attractive in Canada from an economic and social point of view, than for a jurisdiction such as Australia, which could feasibly benefit economically from an automotive industry based on the principles of MFR.

This thesis has attempted to outline a feasible technological pathway and highlight particular policy suggestions that could jointly be used to facilitate a transition to MFR in Canada's automotive industry to improve its long-term economic and environmental sustainability. However, the likelihood of such a transition receiving the necessary support it requires does not appear to be very high, at least within the foreseeable future. It is far more likely that both industry and government will aim for more incremental adjustments that do not diverge too far from the current structure of the industry. It could be argued that the environmental benefits of MFR should be given more weight from the point of view of increasing sustainability in the automotive the industry; however, the political reality it that economic imperatives will always be placed ahead of environmental benefits. For a dramatic socio-technical transition to occur in the automotive industry, there would most likely have to be major economic, social, and environmental shocks, simultaneously at both the regime and landscape level to create the necessary pressures required to create a window of opportunity for MFR to compete directly against the dominant paradigm in mainstream markets.

10.4 Micro-Factory Retailing *Lite*

Despite the relatively low probability that a full-scale transition to MFR and innovative business models enabled by PSS will occur in the foreseeable future, it does not mean that each of the components presented in this thesis won't individually have a disruptive impact on the automotive industry. For instance, many industry analysts anticipate that as battery prices approach parity with ICEs, there is likely to be a significant market shift towards EM, which will have significant impacts on its own. Although it seems rather unlikely that automakers will soon be manufacturing 3D printed automotive bodies or structures out of thermoplastics, the rapid prototyping of parts has become a key tool for improving manufacturing flexibility, reducing time-to-market, and avoiding the high capital cost of pre-production tooling. The industry may not embrace AM to the extent described in this thesis. Rather, it is much more likely that 3D printed production parts become ever more common for use in specialised or replacements parts. The impacts of this may be less disruptive overall, but are sure to affect how VMs conduct their business. The same will likely be true for business model innovation as new entrants and technology firms force incumbent VMs to change their value proposition to remain competitive.

In essence, it is quite possible that global VMs will adopt aspects of what was proposed in this thesis to create their own *lite* version of MFR to enhance their economic and environmental sustainability without necessarily achieving the full benefits of MFR to their greatest extent. For instance, the global automotive industry's current propensity for regionalization of production capacity in emerging markets due to shifting market demand could represent the full extent to which the industry will approach a localized production strategy. It does not appear as though the industry has the appetite for further localization at a finer scale. A future lite version of MFR may conceivably be possible within the industry's current distribution of assembly plants given the extent to which VMs have already been regionalizing their operations in areas with the highest anticipated future demand as they experiment with new production technologies on the assembly floor to maximize operational flexibility.

Alternatively, it is possible that micro-factories could develop in Canada without necessarily challenging or replacing the centralized mass production paradigm. Local Motors founder Jay Rogers acknowledged that digitally enabled micro-factories could act as both flexible manufacturing facilities for highly customized products but also act as an incubation site for testing new ideas before investing in full scale mass manufacturing (Buchanan, 2014). In his explanation, Rogers used a rental car company as an example (however, other MaaS business models or fleet operators could be substituted here), to suggest that mass production may in fact be more suitable to particular business models that do not require the same degree of customization or product variation to generate demand (Buchanan, 2014). Perhaps MFR will not replace mass manufacturing but instead compete alongside it at a different scale within the automotive ecosystem and fulfill a very different need. If, for instance, MaaS and autonomous vehicles did affect the demand for individual vehicle ownership, MFR could be used to satisfy the remaining demand for this market segment, which would likely place personalization, performance, and design much higher on their priority list while also potentially exhibiting less price sensitivity. Theoretically, MFR could have a role in a future, more sustainable mobility ecosystem to satisfy a particular sub-set of the vehicle market, that is willing to pay a premium for a unique product and ownership experience, without needing to replace mass automobile manufacturing, which may be required to satisfy other market demand including fleet operators and mobility services such as PSS.

10.5 Future Research

Two of the most prominent challenges for the MFR concept are likely its novelty and its radical departure from the status quo. For instance, the MFR model fundamentally changes the economics of the automotive industry by situating retailing activities at manufacturing sites (under the direct control of VMs), and emphasizing downstream revenue opportunities through the use of innovative, service-oriented business models. Moreover, it proposes dramatic improvements to the industry's environmental performance through dematerialization and circular material cycles, and lower life cycle environmental costs. Many aspects of the MFR model, including the technologies proposed in this thesis to facilitate the industry's transition in this direction, already exist in some form within the current automotive paradigm. Nonetheless, the MFR concept has yet to be fully executed and thus remains theoretical in nature. As such, future empirical research should focus first on how the vision presented by MFR can be operationalized and, based on those findings, gain new insight into its benefits—but also its potential challenges.

Second, should any of the innovative companies studied in this thesis manage to become mainstream, they could be profiled once again to uncover what strategies and/or solutions were most and least effective in terms of accelerating the adoption of novel innovations and improving sustainability.

Third, given the automotive industry's well-documented history of prioritizing incremental change and resisting more radical or systemic changes, research should be conducted to uncover effective policy interventions to facilitate more noteworthy innovation and aid in the industry's transition towards greater sustainability. Governments should develop appropriate innovation strategies that specifically target the automotive industry and focus on sustainability improvements. Just as policy researchers have studied the effectiveness of pro-plug-in electric vehicle (PEV) policies, researchers should begin to study the efficacy of policies aimed at encouraging sustainable innovation in the automotive industry.

Fourth, a future sustainable mobility paradigm that includes EM will inevitably engage governments at all levels as stakeholders; as such, governments must prepare for a future role within sustainable mobility ecosystems and learn how to best foster such a transition. The multi-level perspective (MLP) could be used to uncover appropriate policy measures to guide the industry's transition towards improved economic and environmental sustainability regarding MFR. Furthermore, MLP could be utilized to hypothesize what major changes in the automotive ecosystem could be expected, and potentially how quickly they might occur.

A fifth opportunity for future research could be conducting a detailed analysis of the economic and environmental impact of MFR in Canada, including a profile of the individualized impacts for each province. The impacts of MFR in Canada will most likely be asymmetric across the country, given the industry's current concentration in Ontario, as well as differences in the distribution of population—both of which are likely to affect the operationalization of MFR in less densely populated areas. A suitable mechanism for answering these types of questions and exploring the geographic suitability of localized micro-factories in Canada in more detail would be a simulation analysis to generate hypothetical scenarios with differing parameters (e.g., population, production volume, demand, etc.) for the distribution of micro-factories to examine changes in their economic, social, and environmental impacts. The results would shed light onto the potential opportunities and challenges that Canada could face if it was indeed successful in transitioning to a MFR-style system of automotive production and distribution.

Research in this area should be ongoing as the process of system innovation is dynamic and complex, suggesting that the economic impact of a large scale transition in the automotive industry is likely to evolve as the industry moves through a series of potentially intermediate steps before arriving at a new, more sustainable, equilibrium state.

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