# THE HYBRID-ELETRIC VEHICLE LIFECYCLE: EMISSIONS FROM THE TAILPIPE AND THE NICKEL METAL-HYDRIDE BATTERY

by

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B.A.Sc. (Hons) University of Waterloo, 2005

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(Resource Management Environmental Studies)

THE UNIVERSTIY OF BRITISH COLUMBIA

August 2007

**ABSTRACT**

This 'manuscript-based' thesis investigates the airborne environmental releases over the lifecycle of hybrid-electric vehicles (HEV) as compared to equivalent conventional internal combustion engine vehicles (ICEV). The first manuscript (Chapter 2) (i) quantifies the flow of nickel in the North American economy, (ii) estimates the impact of HEV production on nickel flows, and (iii) assesses the lifecycle environmental and human health impacts from HEV battery production. The research methodology consists primarily of synthesizing information and reconciling data available from multiple sources; tabulating nickel emissions data; using material balance calculations to "close the loop"; and interviewing industry experts to reconcile discrepancies. The results show that small amounts of nickel are released to the air from the nickel-mining phase, with larger emissions of nickel expected from recycling of the HEV battery. The human health effects of excess nickel releases are likely to be small. The analysis behind the second manuscript (Chapter 3) explicitly quantifies use-phase air pollution emissions improvements. The methodology involves calculating use-phase tailpipe and fuel cycle emissions over the useful life of an HEV and comparing them to an equivalent conventional ICEV using in-use emissions testing data and regulatory estimates. The results show that HEVs provide modest tailpipe emissions improvements over ICEVs in the use-phase; however current testing methods do not accurately capture the real world behaviour of HEVs. It is found that the majority of emissions improvements of HEVs over ICEVs are achieved in the cold-start phase of the driving cycle, with total use-phase improvements of 33% for carbon dioxide, sulfur oxides, and particulate matter, reductions in carbon monoxide emissions on the order of 50%, hydrocarbon emissions improvements of 25%, and more modest nitrogen oxide benefits over different scenarios of vehicle usage and cold-start frequency. Combined, these manuscripts quantify the human health and environmental impact of the air pollutant releases over the HEV lifecycle and find that the effects of the material extraction and post-use phases are more than compensated for in the use-phase relative to an equivalent conventional ICEV.

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**ACKNOWLEDGEMENTS**

I sincerely thank Milind Kandlikar for the guidance, support and insight he has consistently provided over the past two years. This research has also benefited significantly from the additional input supplied by Hadi Dowlatabadi. In addition, I am indebted to Mark Jaccard, John Robinson, Mory Ghomshei, Terre Satterfield, and Heather Maclean for their contribution to the knowledge and skills I have gained throughout this degree, which have in turn been employed in this thesis. The numerous discussions and collaborations that have occurred over the past two years with Conor Reynolds and other colleagues have also greatly influenced the thought behind this work. I remain indebted to the Auto21 Network of Centres of Excellence for its generous financial support. Lastly, I am immensely grateful for the encouragement, understanding, and unending moral support provided by Jonathan and my family, Allan, Charlotte, Melanie, and Angela.

## CO-AUTHORSHIP STATEMENT

Dr. Kandlikar co-authored the manuscripts presented in Chapters 2 and 3 of this thesis. In both papers, Dr. Kandlikar contributed to the research design and to the manuscript review. My contribution to the manuscripts presented in Chapters 2 and 3 and the overall thesis included:

- Identification and design of the research program (with guidance from Milind Kandlikar);
- Research;
- Data analysis;
- The literature review for all manuscripts and additional information in this thesis; and
- Manuscript preparation, review and editing.

# CHAPTER 1: INTRODUCTORY CHAPTER

## 1.0 INTRODUCTION

This thesis investigates the lifecycle of the hybrid-electric vehicle (HEV). The 'manuscript-based thesis' format (specified by the Faculty of Graduate Studies) was adopted to utilize the two completed journal manuscripts in which the research is documented. The first manuscript, contained in Chapter 2, investigates the environmental and human health implications of the lifecycle of the nickel metal-hydride (NiMH) battery contained in HEVs. The analysis quantifies releases of nickel to the air over the HEV lifecycle, from the extraction of primary materials to the subsequent recycling of the batteries, and compares them to those from an equivalent conventional internal combustion engine vehicle (ICEV). The study skips over the use-phase of the HEV lifecycle as there are no releases associated with the battery during vehicle operation. Consequently, the use-phase topic becomes the focus of the second manuscript, included as Chapter 3, which compares criteria air pollutant emissions over the use-phase of an HEV to those of an equivalent conventional ICEV. A version of the Chapter 2 manuscript has been submitted to the *Journal of Industrial Ecology* and a version of the Chapter 3 manuscript is planned to be submitted to *Transportation Research Part D: Transport and Environment.*

This introductory chapter provides an overview of the research topic and the context for the remaining chapters. It includes a brief history of automotive pollution reduction efforts in North America, an overview of HEVs – their purpose, how they work, and their potential future in North America, an overview of the NiMH battery lifecycle, as well as an overview of the lifecycle assessment concept in the automotive context and finally a short summary of previously conducted HEV life cycle assessment studies. The information in this chapter is supplementary to that which is presented in Chapters 2 and 3. A discussion of the research objectives and hypothesis concludes this section.

## 1.1 HISTORY OF AUTOMOTIVE POLLUTION REDUCTION

Motor vehicle tailpipe emissions are a major air quality and, consequently, human health concern. Four vehicle emissions of interest to regulators (termed criteria air pollutants) in the United States (US) are hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM). HC emissions are the result of unburned or partially burned fuel molecules; they are potentially carcinogenic and play a role in the formation of ground-level ozone, a major component of smog. CO

is a poisonous gas that impairs the flow of oxygen to parts of the human body, including the brain [1]. NOx is a precursor to smog and PM, which can intensify respiratory problems in humans; it also can cause acid rain and harm aquatic environments [1]. Finally, PM may induce carcinogenic as well as detrimental respiratory and cardiac effects in humans [1].

With the goal of reducing exposure to these harmful pollutants, vehicle emission standards have been enforced and vehicles in the US and Canada have progressively gotten cleaner as a result [2]. Beginning in the early 1970s with the Clean Air Act [3], vehicle emissions standards have become increasingly more stringent over time and vehicles continue to meet the requirements; thereby emitting a lower level of pollutants per mile traveled. For example, light duty vehicles (LDV) in the US must meet the Environmental Protection Agency's (EPA) federal Tier 2 emissions regulation which has lower maximum allowed levels of pollutants than its predecessor, the Tier 1 regulation.

In addition to the EPA's federal standards, the California Air Resources Board (CARB) established even more stringent vehicle emission standards for LDVs driven in the state of California because of its unique air quality problems. In September 1990, CARB introduced the Low Emission Vehicle I (LEV-I) emission standard, whereby a minimum percentage of vehicles sold in California were to be certified in low- and zero-emission categories [4]. Included in the regulation was the Zero-Emission Vehicle (ZEV) Mandate, whereby an increasing percentage of manufacturer sales of new LDVs in California were to be ZEVs [4]. In order to meet these emission requirements, automotive manufacturers and government research concentrated on emissions improvements in ICEVs as well as developments in battery-electric vehicles (BEV) and related components [5,6]. The short range of BEVs was foreseen to be an impediment to their success outside of niche markets so in the early 1990s, research in HEV technology intensified. By combining a BEV with an ICEV, the HEV achieved low tailpipe emissions without the range issues. Although best known for their superior fuel economy today, emphasis during the early stage of HEV development was placed on achieving low emission levels [5], thereby making the technology a consequence of the demand for improved criteria pollutant emissions from automobiles rather than lower fuel consumption.

## 1.2 UNIQUE FEATURES OF HYBRID ELECTRIC VEHICLE OPERATION

The general definition of an HEV is a vehicle in which propulsion energy is available from two or more types of energy stores or sources and at least one of them can deliver electrical energy [8]. Most of the

commercially available HEVs are equipped with a gasoline internal combustion engine (ICE) and an electric battery which powers an electric motor. Modern mass-produced HEVs use NiMH batteries, which can recover and store energy normally lost as heat by capturing kinetic energy while cruising, driving downhill, and braking through a process called regenerative braking. The extra power provided by the electric motor allows for a smaller, more efficient ICE [8]. Part of the power from the ICE, in turn, is used to create electric power in a generator, which can either be used by the electric motor or stored in the battery for future use. At certain points in the drive cycle, such as when idling or traveling at low speeds, an HEV with idle-off and/or electric-only capabilities can use its electric motor instead of its gasoline powered ICE, which can provide significant fuel economy and emissions-reduction benefits.

There are two classifications of full-HEVs: parallel and series. The main difference between the two is how the motive force is provided to the wheels. The parallel configuration enables both the battery- and generator-powered electric motor and the ICE to assist in powering the wheels. In the series HEV, the ICE- and battery-powered generator and the battery provide power to the electric motor, which alone provides motive force to the wheels [9]. The Toyota Prius, currently the best-selling HEV on the North American market, is a combination of the two configurations as both the ICE and electric motor are able to drive the vehicle independently [10].

## 1.3 ENVIRONMENTAL BENEFITS OF HYBRID-ELECTRIC VEHICLES

In urban settings, the personal automobile is the single greatest polluter and gasoline consumer [1]. Hybrid technology is a proven means to improve the fuel economy and reduce the greenhouse gas and criteria air pollutant emissions of light duty passenger vehicles [11], which can contribute to lowering the impact automobiles currently have on the environment. Oil is a non-renewable resource with increasing global demand from automotive and other applications. Currently, transportation is responsible for 68% of the total US petroleum consumption [12], making vehicles substantial contributors to the problem of oil dependency. An unavoidable consequence of burning carbon-containing fuels such as gasoline is the production of carbon dioxide ($CO_2$), which is a greenhouse gas (GHG) and contributes to climate change. Transportation is the largest $CO_2$-producing sector in the US, and over 60% of those emissions are produced by the burning of motor gasoline [12]. Further, in 2002 transportation was responsible for nearly one half of smog-forming volatile organic compounds

(VOC) emitted, more than half of the $NO_x$ emissions, and more than 75% of CO emissions in the US [12].

### *1.3.1 Improved Fuel Economy*

In automotive applications, the cessation or reduction of gasoline combustion and consequent $CO_2$ emissions can be achieved either through fuel-switching, advanced technology, efficiency improvements, and/or less driving [11,13]. HEVs employ the first three strategies by consuming electricity as fuel and using the hybrid powertrain to improve efficiency.

In general, HEVs reduce fuel consumption as compared to equivalent conventional ICEVs by having higher energy efficiency and using the electric motor to either supplement or replace power from the ICE. The smaller ICE decreases under-utilization inefficiencies because it has the ability to compensate its lower gasoline-fueled power with electric motor output. By using the electric motor in place of the ICE in certain points during the drive cycle, less fuel is consumed and none is wasted on idling if the vehicle has idle-off capability [9]. Also, regenerative braking is a means to improve efficiency by recapturing waste energy that is otherwise lost and can be used for motive purposes [9,14]. Through these measures, HEVs achieve superior fuel economy over conventional ICEVs thereby producing less $CO_2$ and lowering dependency upon a nonrenewable resource.

### *1.3.2 Fuel Cycle Emissions Reduction*

Fuel pumped into the gas tank of a vehicle has emissions associated with it that occur upstream of the distribution infrastructure. The exploration and production of crude oil, the refining of petroleum, and the transportation of gasoline to the refueling station are all steps that produce emissions before the fuel is even combusted in an automotive engine [15]. For every litre of gasoline consumed in a vehicle, there is a certain mass of fuel cycle air emissions ($CO_2$, CO, HC, $NO_x$, sulphur oxides, and PM predominantly) that are released upstream. Fuel cycle emissions from a vehicle are therefore a direct function of its fuel economy. As fuel economy improves, these upstream emissions are reduced, however as tailpipe emissions also get lower, they become more important to account for in order to accurately quantify pollutant emissions produced over the lifecycle of a vehicle [9,15].

### *1.3.3 Air Pollutant Emissions Savings*

Air pollutant emission improvements are achieved by HEVs primarily via two means: increased efficiency and advanced emission control technologies. The most popular HEV, the Toyota Prius,

meets Environment Canada's and the EPA's Tier 2 Bin 3 emission standard. It is also certified to the most strict emission standard in the world for a gasoline-powered automobile, the Advanced Technology-Partial Zero Emission Vehicle (AT-PZEV). According to Toyota, the Hybrid Synergy Drive (HSD), its third generation gas/electric hybrid powertrain technology produces nearly 90% fewer smog-forming emissions than a conventional ICEV [16].

## 1.4 THE HYBRID-ELECTRIC VEHICLE MARKET

The progressive tightening of vehicle emissions standards over time has caused retail prices of vehicles today to be approximately $1K higher than they would be without emissions controls such as the catalytic converter [17]. For hybrid technology, Toyota customers currently pay a premium of $6K-$9K for an HEV over a comparable ICE vehicle[1] [18]. Performance or luxury HEVs, such as those produced by Lexus, come at a higher premium, from $10K – $17K[2] [19].

Despite higher initial investments, the HEV market continues to expand both in terms of annual sales and models offered. In 2005, HEV sales represented less than 1.2% of new LDV sales in the US [20; 21], a 145% increase over 2004 sales. Last year sales continued to increase, although at a slighter lower rate. 2006 HEV sales accounted for 1.5% of new LDV sales in the US [20], a 20% increase over the previous year. The Toyota Prius was one of the first two HEVs on the North American market and has maintained a strong market share since its introduction in 2000. Last year was the first year its sales amounted to less than one half of all HEV sales in the US (42%) and it was also the first year the immediately popular Toyota Camry Hybrid was sold. Beginning in 2003 with the Honda Civic Hybrid, the number of full-HEV models available expanded in order to provide more choice and to cater to driver demand for larger, more powerful, and more spacious vehicles. Besides those already mentioned, full-HEV that were sold in North America last year included two performance sedans, the Honda Accord Hybrid and the Lexus GS450h, and three sport utility vehicles (SUV), the Lexus RX400h, the Toyota Highlander Hybrid, and the Ford Escape Hybrid.

Various HEV sales projections systematically predict an increasing market share over time, the extent varying upon the study and/or researchers, but most are modest projections mainly due to the higher

[1] The 2007 Toyota Camry is $6100 more than the Toyota Camry LE. The Toyota Highlander Hybrid is $6380 more than the Toyota Highlander 4WD V6. The Toyota Prius is $9380 more than the Toyota Corolla LE.
[2] The Lexus RX400h is $10700 more than the Lexus RX350. The Lexus GS450h is $17150 more than the Lexus GS350 RWD.

cost of the vehicles. On that note, Toyota aims to cut its HEV price premium in half by 2010 (to less than US$2K) [21]. Greene projects HEVs will reach a ten percent market share by 2012, however their higher price will put a ceiling of 50% over the long term [23]. JD Power and Associates are a bit less optimistic and project a peak HEV market share of 4.2% in 2010 [24]. One study at the other end of the spectrum envisions HEVs taking up 85% of new vehicle sales by 2030 [25]. As mentioned previously, the number of HEV models on the market has increased substantially. 1999 was the first year an HEV was put on the US market; the only model available was the Honda Insight, a two-seater that is no longer sold. By 2006 there were eleven HEV models available, including SUVs, luxury performance vehicles, and mild HEVs. At least nine more models (all midsize, truck, or SUV varieties) are slated for release over the next two years [2] and JD Power proposes that the total number of models could rise up to 52 by 2012 [24].

## 1.5 TRENDS IN HYBRID-ELECTRIC VEHICLE TECHNOLOGY AND FUEL ECONOMY

Over the last 30 years, average vehicle weight and horsepower has increased, and average 0 to 60 mph acceleration time has been reduced, while fuel economy has remained relatively stagnant within the LDV fleet. Such trends suggest that technical innovation and improvements in engine, transmission, and powertrain technologies in the average conventional LDV (of which light trucks increasingly occupy a larger proportion) have been applied towards increasing performance and weight accommodation, rather than improving fuel economy [21]. EPA estimates that had the new 2005 LDV fleet had the same distribution of performance and weight as in 1987, it could have achieved about 24% higher fuel economy.

A similar trend is being observed in the HEV fleet. From 2000 to 2006, the sales-weighted average HEV in the US LDV fleet has increased its curb weight by 30%, its power has increased by 60%, its gasoline engine displacement has grown by 43%, its 0 to 60 mph acceleration time has decreased by 20%, and its fuel consumption has increased by 15% [26]. Since 2004, the first generation Toyota Prius has been replaced with a larger, more powerful second generation version and a number of SUV and luxury/performance HEVs have also entered the market. Although HEVs maintain a fuel economy improvement over equivalent ICEVs, the trend towards heavier and more powerful hybrid vehicles is "eroding the fuel consumption benefit" [26].

## 1.6 COMPONENTS OF THE AUTOMOTIVE LIFE CYCLE ASSESSMENT

The environmental implications of an automobile are not limited to the fuel it consumes and the emissions it produces between the showroom and the shredder. The entire lifecycle of an automobile, from the extraction of the materials used in its manufacture to the recycling of its valuable parts, has potential impacts upon human health and the environment. There are four main stages in an automobile's lifecycle and all can be associated with discharges to the environment and in order to effectively assess the impact of a vehicle, its complete lifecycle needs to be considered [15].

- Material extraction phase – primary materials, such as metals, are extracted from the earth, yielding releases to the air, water, and land;
- Manufacturing phase – energy use, environmental discharges, and the use of resources are potential environmental effects felt by the construction and assembly of automotive parts;
- Use phase – emissions from this phase are primarily produced by the tailpipe during vehicle use, but emissions associated with the production of fuel, as well as any discharges from vehicle servicing are also included in this stage;
- Disposal and/or recycling phase - adding waste to landfills and emissions from recycling facilities are potential environmental releases in this stage.

The resource use and toxic discharges of the disposal/recycling phase are small compared to the production and use phases, with the use phase being the most important in terms of environmental discharges [15].

## 1.7 PREVIOUS HYBRID-ELECTRIC VEHICLE LIFE CYCLE ASSESSMENTS

A number of life-cycle assessments have examined whether HEVs are economically beneficial to their owners, taking into effect monetized environmental benefits, such as reductions of GHGs, air pollution emissions, and fuel consumption.

Based on hybrid sales between 1999 and 2006 as well as sales projection studies, Turrentine et al (2006) [11] estimate the fuel consumption and air pollutant benefits of HEVs over their conventional ICEV counterparts. Using scenarios of different HEV types and market shares, they calculate oil consumption and pollution production reductions of the 2010 hybrid fleet. They calculate the

percentage reduction of fuel used and pollution generated of each HEV model over its conventional equivalent (where a conventional equivalent exists, for example, the Toyota Prius was compared to the Toyota Corolla) per mile of travel multiplied by the HEV market share. They perform ADVISOR (ADvanced VehIcle SimulatOR – one of the most widely used computer simulation tools for HEVs developed at the National Renewable Energy Laboratory) simulations to estimate the per-mile reductions in fuel use and emissions of $CO_2$, HC, CO, and NOx. They find that on average, HEVs reduce fuel use by 35% and lifecycle emissions of GHGs by 30% over their conventional counterparts.

Lipman and Delucci (2006) [27] compare the vehicle manufacturing costs, retail prices, and vehicle lifecycle costs of HEVs and conventional vehicles at high production volume using twenty five different scenarios of vehicle type and hybridization level. This analysis is performed using a cost-analysis spreadsheet linked with a performance analysis based on the ADVISOR model. Lifetime social costs of HEVs are also explored in order to determine whether the greater private costs of these vehicles are outweighed by their provision of social benefits (like air quality improvements for example). The authors find that a combination of *advanced* vehicle improvements (such as vehicle weight and drag reduction and variable-valve-timing) and *mild* vehicle hybridization has lifetime costs closest to the baseline vehicles. They also find that the inclusion of social costs into the HEV lifecycle makes them more economically attractive.

Weiss et al (2000) [28] assess and compare a number of representative future technologies (spark ignition ICEs, compression ignition (diesel) ICEs, hybrid-electric ICEs, fuel cell hybrids, and battery-electric vehicles) using a variety of fuels (gasoline, diesel, Fischer-Tropsh synthetic diesel, methanol, compressed natural gas, hydrogen, and electric power) and compare them to an "evolved baseline" passenger car in terms of lifecycle energy use, lifecycle GHG emission production, and lifecycle consumer cost per unit of distance driven. The authors find that hybrid vehicles are the most efficient and lowest-emitting technologies assessed. In general, ICE hybrids appear to have advantages over fuel cell hybrids with respect to life cycle GHG emissions, energy efficiency, and vehicle cost.

Wang et al (1997) [29] estimate fuel-cycle and vehicle-cycle energy use and emissions production using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model developed at Argonne National Laboratory (ANL) and fuel economy and emissions production using the ADVISOR model for a grid-independent series HEV that operate like a conventional vehicle and one that operates as an electric vehicle part of the time. Comparison with a steel-intensive and an

aluminum-intensive conventional ICEV is performed along with an examination of two battery types (lead-acid and nickel-metal hydride). The authors find that both hybrids examined use significantly less energy than a similar conventional vehicle (33 to 66% of equivalent conventional vehicle in urban driving cycles for energy and petroleum use and GHG emissions).

Lave and Maclean (2001, 2002) [30,31] explore the case for HEVs from an economic perspective by comparing the Prius to the Corolla in terms of air pollution, $CO_2$, and fuel savings over its use phase. They conclude that the monetary value of the fuel savings and reduction in pollutant emissions achieved by the Prius over the Corolla is less than the initial investment required for its purchase. Using emissions testing data provided by Toyota, social valuation costs of pollutant reductions from other studies, and fuel consumption estimates from the EPA, the authors find that the Prius offers reductions in fuel consumption and air pollutant and fuel cycle emissions, however not enough to make the purchase of the vehicle economically worthwhile.

Of the literature reviewed, there is a distinguishable emphasis on lifecycle economics and fuel consumption. There is therefore a weakness in the present state of research in this field with respect to quantifying air pollution reductions and assessing the overall impact of those improvements over the lifecycle of the HEV. More specifically, there are no studies of nickel and associated emissions resulting from the HEV NiMH battery lifecycle.

## 1.8 RESEARCH FOCUS AND HYPOTHESIS

HEVs employ vehicle components that are different from those in ICEVs such as advanced batteries, electric motors, and other electronic controls which cause them to have different energy and emissions impacts over their lifecycles. New technologies, such as HEVs, are often associated with tradeoffs such that local environmental improvements come at the cost of transferring harmful discharges elsewhere. The manuscripts contained in this thesis focus upon airborne releases to the environment and attempt to quantify the difference between those emitted throughout the HEV lifecycle in comparison with the ICEV lifecycle.

The aim of the combined manuscripts is to examine whether the impact of the additional nickel and associated releases emitted to the environment from the HEV lifecycle is outweighed by emission

reductions in the use phase as compared to an equivalent conventional ICEV. Does the average HEV offer an overall impact or improvement upon the environment when compared to the average ICEV?

The first manuscript presented in Chapter 2 evaluates the nickel and associated releases over the lifecycle of an average sedan-sized HEV as compared to an equivalent ICEV. The second manuscript presented in Chapter 3 evaluates the criteria air pollutant emissions over the use-phase of the HEV lifecycle as compared to an equivalent ICEV by contrasting specifically a Toyota Prius with a Toyota Corolla. By combining the findings of these two manuscripts and performing an evaluation of their respective impacts to human health and the environment, Chapter 4 attempts to address this research question.

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# CHAPTER 2: HYBRID-ELECTRIC VEHICLES AND THE MATERIAL FLOWS OF NICKEL

**NOTE:**

A version of this paper has been submitted for publication. Jones, K., Kandlikar, M. Hybrid-Electric Vehicles and the Material Flows of Nickel, Journal of Industrial Ecology, 2007. Awaiting acceptance to journal.

## 2.0 INTRODUCTION

Hybrid-electric vehicles (HEV) have become an increasingly visible presence on roads in North America. In order to achieve fuel economy benefits HEVs integrate a smaller internal combustion engine with an electric motor, supplementary electronics, and a large, high-powered rechargeable battery. With HEV market penetration predicted to rise from less than 1% in 2004 to between 3.5% and 10% over the next 5 years [1, 2], a growing number of these vehicles will be manufactured and subsequently recycled at the end of their useful lives. Early electric vehicles (EVs) were equipped with lead-acid batteries (LABs) but more recently, nickel metal-hydride (NiMH) batteries[3] have been deemed superior for HEV application [4, 5] for reasons such as a lower weight burden, higher energy density, and longer range [4].

HEVs provide environmental improvements in the use-phase [6] particularly by reducing carbon emissions by an average of 6 tons over vehicle lifetime [7]. However new technologies often involve trade-offs, and improvements may come at the cost of transferring other harmful discharges elsewhere [8]. From a materials cycle perspective, the major difference between an HEV and an equivalent conventional internal combustion engine vehicle (ICEV) is an increase in the use of nickel associated with the lifecycle of the NiMH batteries. This study aims to: (i) investigate the impact of HEV batteries on nickel material flows in North America, (ii) assess nickel releases over the lifecycle of an HEV as compared to a conventional ICEV in the North American context, and (iii) quantify the environmental impact of excess nickel production and release attributed to HEV batteries. Lifecycle studies comparing the greenhouse gas, air pollutant emissions, and fuel consumption of ICEVs versus HEVs have been

[3] Nickel cadmium (NiCd) batteries are attractive to applications requiring portable rechargeable chemical energy given their low cost, long life cycle, and high charge /discharge rates [3]. However they are potentially toxic [3] and NiMH and lithium ion batteries are therefore replacing them in many applications.

performed [7,8]; however no study has investigated releases of nickel and associated toxics over the life cycle of an HEV.

The methods used in this paper consist primarily of synthesizing information and reconciling data available from multiple sources; tabulating nickel emissions data; using material balance calculations to "close the loop"; and interviewing industry experts to reconcile discrepancies. The paper begins (Section 2.1) with an assessment of the flows of nickel in the North American economy. Baseline values for nickel production and consumption by sector are established by using mineral commodity data (2004) from the United States Geological Survey (USGS) and Natural Resources Canada (NRCan). In Section 2.2, end-use consumption and fate of nickel within the North American automotive industry is calculated, with a specific focus on the HEV NiMH battery. Section 2.3 calculates the airborne releases of nickel, criteria pollutants, and toxics associated with the lifecycle of the HEV NiMH battery. The analysis is concluded with an assessment of the human health and environmental impacts of HEV related nickel flows in North America.

## 2.1 NICKEL FLOWS IN NORTH AMERICA

Within the North American economy, nickel is available for consumption from processes of primary production (mining and refining), secondary production (scrap recycling), imports, and the use of stockpiled resources. Nickel is expended within the economy through the commercial consumption of nickel end-uses, exports, and releases to the environment. Nickel recycling gives this flow a cyclical trajectory, as captured in Figure 2.1 - a scaled schematic of nickel production, consumption, and recycling volumes for North America in 2004. The height of each box in the figure is proportional to the amount of nickel produced, used or lost in the annual cycle of material flows. Data for Figure 1 was synthesized from national surveys of metal usage in Canada and the US respectively [9,10,11]. End uses of primary and secondary nickel are quantified in greater detail in Table 2.1. From a materials cycle perspective, the flows of nickel in North America shown in Figure 2.1 have the following key features:

- **Primary and Secondary Production:** The primary production of nickel is roughly equally divided between production from domestic mining and imported nickel ore. The majority of primary nickel (68%) produced in North America is exported, while the remainder is locally consumed. Secondary production of nickel is similar in mass to domestically mined nickel, but

only 37% of secondary nickel production is exported. Secondary nickel production is primarily a result of the recycling of steel scrap. Secondary imports constitute less than 10% of secondary production.

- **End Uses:** Of the nickel consumed in domestic manufacturing greater then 50% is primary nickel. Steel accounts for two-thirds of all nickel consumed in North America. Roughly half of end-use primary nickel is used for steel production, while the rest is used for alloys, electroplating and other applications. By contrast more than 90% of the nickel in the secondary production loop is cycled back into steel. As observed in Table 2.1, some applications of nickel (nickel alloys, superalloys, electroplating, and chemical uses) almost exclusively use primary nickel. These applications account for roughly 40% of all primary nickel used.
- **Losses and Dispersal:** Since steel is a valuable commodity, a relatively small proportion leaves the recycling loop, in fact over 90% of steel is recycled. Consequently, less than 10% of nickel used in steel is lost from the recycling loop. Of the remaining third used in non-steel applications, 66% is cycled back into the secondary loop. In total, greater than 80% of all nickel consumed in the North American economy is recycled.

**Table 2.1 North American Primary and Secondary Nickel Consumption by End-Use in 2004**

| Nickel End - Use | Primary | | Secondary | | Total | |
|---|---|---|---|---|---|---|
| | (000 t) | wt.% | (000t) | wt.% | (000t) | wt.% |
| Steel | | | | | | |
| Stainless and heat resistant | 46.0 | 45.1 | 76.4 | 86.8 | 122.4 | 64.4 |
| Alloys, excludes stainless | 3.0 | 2.9 | 0.6 | 0.7 | 3.6 | 1.9 |
| Ni-based alloys | 12.0 | 11.8 | 0.0 | 0.0 | 12.0 | 6.3 |
| Superalloys | 15.0 | 14.7 | 0.2 | 0.2 | 15.2 | 8.0 |
| Electroplating | 13.0 | 12.7 | 2.5 | 2.8 | 15.5 | 8.2 |
| Other (including batteries) | 3.7 | 3.6 | 4.5 | 5.1 | 8.2 | 4.3 |
| Ni-Cu and Cu-Ni alloys | 3.0 | 2.9 | 3.5 | 4.0 | 6.5 | 3.4 |
| Chemicals and chemical uses | 6.0 | 5.9 | 0.0 | 0.0 | 6.0 | 3.2 |
| Cast Iron | 0.1 | 0.1 | 0.3 | 0.3 | 0.4 | 0.2 |
| Electric, magnet, expansion alloys | 0.2 | 0.2 | 0 | 0.0 | 0.2 | 0.1 |
| **TOTAL** | **102.0** | **53.7** | **88.0** | **46.3** | **190** | **100.0** |

Notes:
1. Source: [9, 10].
2. Data assumes that Canada and the US engage in similar nickel end-use consumption distributions.

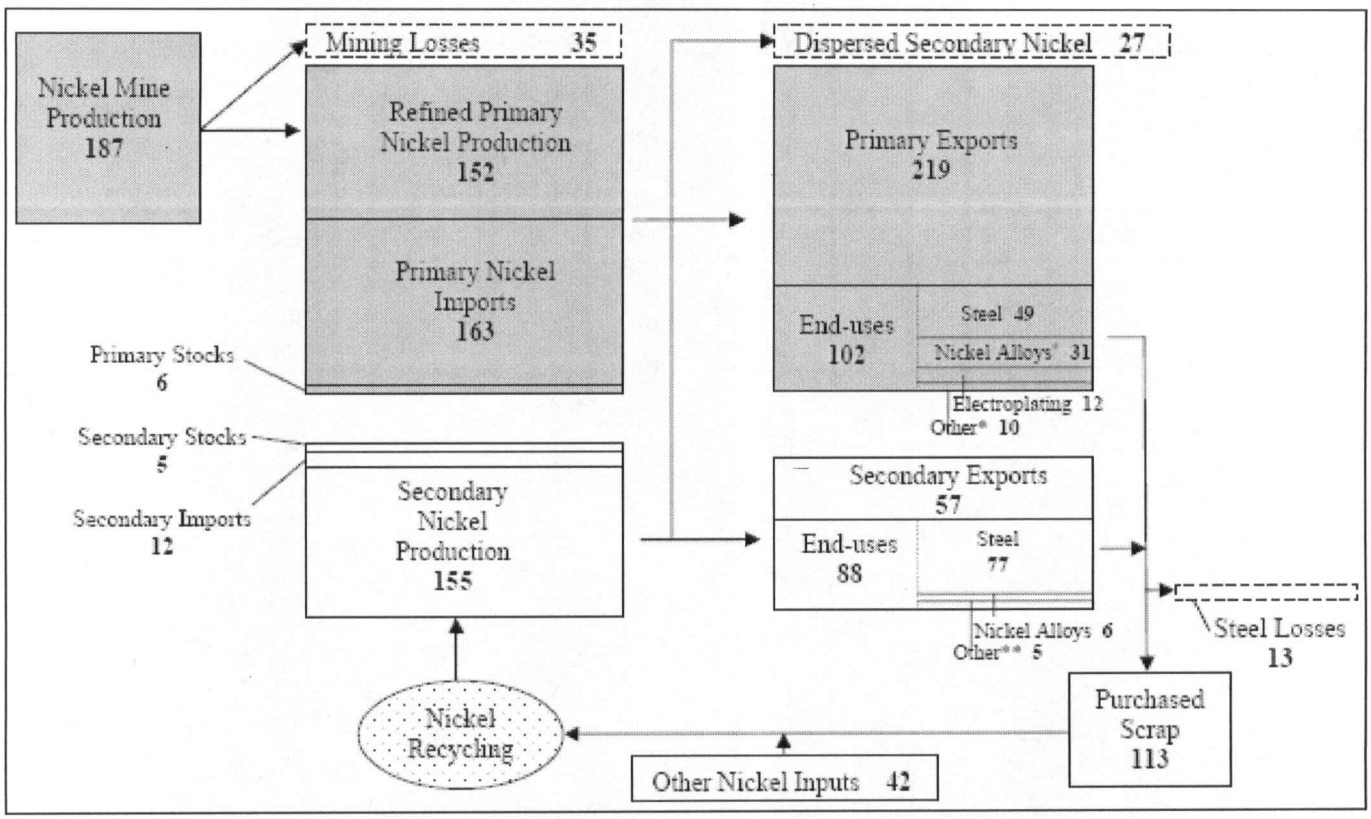


**Figure 2.1 2004 Flow of Nickel through North American Economy (in kilotons)**

Notes:
+ Includes copper-nickel alloys, nickel-copper alloys, and superalloys.
* Includes cast irons, chemical uses, EME alloys, and other applications (includes batteries, catalysts, ceramics, coinage, and other nickel alloys [10]).
** Includes cast irons, chemical uses, EME alloys, electroplating, superalloys, and other applications.

1. Values for imports and exports other than stainless steel may be slightly over-estimated because Canadian data [9] is estimated by weight of material and not nickel content. Canadian imports and exports of stainless steel scrap are multiplied by 10% to estimate nickel content.
2. Canadian secondary nickel production data are confidential and could not be obtained. The calculation above assumes: 8 million tons of steel annually recycled in Canada [11], average nickel content of 1%wt, 10% loss through recycling

## 2.2 NICKEL CONSUMPTION IN THE AUTOMOTIVE SECTOR

This section evaluates the end-use consumption and fate of nickel in the North American automotive industry and provides a quantitative breakdown of primary and secondary automotive nickel contained in automobiles, for both ICEVs and HEVs. Nickel is an essential element of every automobile. In North America, the automotive industry used 12.2% of all nickel consumed in 2004 [15]. This consumption is distributed by automotive nickel end-use in Table 2.2.

**Table 2.2 North American Automotive Consumption of Nickel in 2004**

| Nickel End-Use | North American Automotive Nickel Consumption (by weight)[1] | | |
|---|---|---|---|
| | Total (t Ni)[2] | Fraction of Total without HEVs | Fraction of Total with HEVs |
| Electroplating | 11 378 | 48.6 | 45.7 |
| Stainless and heat resistant steel | 8 737 | 37.3 | 35.1 |
| Alloy steel, excludes stainless | 1 601 | 6.8 | 6.4 |
| Ni-based alloys | 674 | 2.9 | 2.7 |
| Ni-Cu and Cu-Ni alloys | 478 | 2.0 | 1.9 |
| Cast iron | 253 | 1.1 | 1.0 |
| Other | 309 | 1.3 | 1.2 |
| NiMH batteries[3] | 1 482 | - | 5.9 |
| **TOTAL w/o HEVs** | **23 430** | **100** | **-** |
| **TOTAL w/HEVs** | **24 912** | **-** | **100** |

Notes:
1. Assumes Canadian automotive nickel consumption equal to 10% US automotive nickel consumption.
2. Source: [15].
3. Assumes all nickel contained in NiMH batteries mined in North America.

Of the nickel used in the North American automotive industry, roughly half (49%) is used for nickel plating; much of which is used for decorative purposes or for anti-corrosion treatment. Nickel-containing stainless steel is the second largest category of consumption, accounting for 37% of the nickel used in the North American automotive industry. Stainless steels are well suited for structural applications, as well as catalyst supports, exhaust systems, and safety belt springs. Alloy steels, which comprise 7% of the nickel used for automobiles, are mainly employed in gears and drive shafts. Nickel-based alloys (4.9%) are used in a variety of applications including spark plugs, thermostats, turbochargers, wheels, and electronics [16].

NiMH batteries contained in sedan-sized HEVs, such as the Toyota Prius and the Honda Civic Hybrid, weigh 30kg, approximately half of which is refined primary nickel [17,18]. In 2004, NiMH batteries accounted for 6% (1,482 tons) of total automotive nickel consumption. A six-fold rise in the market share of HEVs to 3% by 2010 will result in a 30% increase in total annual automotive nickel consumption due exclusively to the NiMH battery[4]. This is roughly equal to 10% of all primary nickel consumed in North America. Consequently, the diffusion of HEV technology over time is likely to have a substantial impact on future material flows of nickel in the North American economy. In the sections that follow, the impact of increased nickel flows upon releases to the environment is estimated.

[4] This assumes that each HEV uses only one battery in its lifetime. Toyota guarantees its NiMH batteries for at least 8 years (or 100,000 miles) but expects them to last the lifetime of the vehicle [20]. The calculation also assumes that non-battery nickel used in the automobile continues to grow at the same rate as the size of the fleet.

### *2.2.1 Nickel in the Post-Use Phase in the Automotive Sector*

In order to quantify the amount of nickel that is recycled as well as dissipated to the environment we define types of three flows - R1, R2 and R3 Nickel respectively. These flows are graphically represented and quantified in Figure 2.2.

- **R1 Nickel:** Nickel that is recycled back to the automotive sector. This closed loop is achieved mainly through the recycling of stainless and alloy steels and the reuse of large, valuable nickel-containing parts.
- **R2 Nickel:** Nickel that is recycled to non-automotive sectors. A blend of nickel-containing parts is melted down such that the nickel is reduced to a residual element or impurity and becomes incorporated in cycles of aluminum, brass, steel, or other alloyed metals [21].
- **R3 Nickel:** Nickel that is generally dispersed into the environment. Although metal recycling can generally be performed indefinitely with minimal losses [22], full recycling of metals in the automobile life cycle is not achieved mainly due to inefficiencies in material sorting [23]. This nickel ends up in the landfill [18, 21] or is released in small amounts from the recycling processes. This stream is mainly composed of nickel-plated plastic and smaller parts that are missed during dismantling and/or sorting.

In Table 2.3, it is briefly described how the R1, R2, and R3 tonnages are determined. For each category of end-use, a breakdown of post-use disposal and a rationale for each fate are provided. For example, electroplated components are the largest single end-use of nickel. Twenty percent of these plated components are large, valuable and removable parts that can be recycled into the automotive loop through reuse and remanufacturing; 40% are smaller parts that can be incorporated into secondary nickel recycling; while the remainding 40% is in the form of applications that are too expensive to recover. R1, R2, and R3 nickel fractions are estimated for all other end-use categories based on type and size of product, ease of disassembly, and cost of recovery. In aggregate, 81% of nickel is recycled at the vehicle's end of life - 40% recycled back to the automotive sector and 41% is recycled to other nickel applications. Roughly one-fifth of this nickel (19%) is dissipated to the environment (disposed in a landfill or otherwise). The breakdown of the R1, R2, and R3 streams by end-use is illustrated graphically in Figure 2.2.

**Table 2.3 Fate of Automotive Nickel at the End of Vehicle Life**

| Nickel End-Use | R1 Nickel Stream | | R2 Nickel Stream | | R3 Nickel Stream | |
|---|---|---|---|---|---|---|
| | Nickel Fate (%) | Explanation | Nickel Fate (%) | Explanation | Nickel Fate (%) | Explanation |
| Stainless Steel | 70 | High value. High recycling rate. Recycled steel is a major component in new automobiles[1]. | 30 | High value. High recycling rate. | 0 | Negligible losses from recycling. |
| Alloy Steel | 70 | | 30 | | 0 | |
| Ni-based Alloys | 20 | Large, removable parts. | 70 | Highly recyclable metals. | 10 | Small parts. |
| Cu-based Alloys | 20 | | 70 | | 10 | |
| Plating[2] | 20 | One third of nickel-plated metal. Large, valuable, removable parts [26;27]. Some smaller, decorative parts re-used [26;27]. | 40 | Two-thirds of nickel-plated metal. Small, not easily removed parts. Uneconomical to extricate the thin nickel veneer from substrate [26;28]. | 40 | All nickel-plated plated plastic parts. Cryogenic technology for removing nickel from plastic substrates costly and not yet widely used by automotive recyclers [28]. |
| Foundry | 20 | Large, removable parts. | 70 | Highly recyclable metals. | 10 | Small parts. |
| Others | 20 | Contributions to nickel recycling mostly unknown. | 40 | Contributions to nickel recycling mostly unknown. | 40 | Contributions to nickel recycling mostly unknown. |
| NiMH Battery | 0 | Open loop recycling. | 98 | 98% recycling efficiency. | 2 | 98% recycling efficiency. |
| Total w/o HEVs | 42 | | 37 | | 21 | |
| Total w/HEVs | 40 | | 41 | | 19 | |

Notes:

1. Generally, 50% of the steel used in automobiles is secondary depending on market prices and the availability of steel scrap [14;26;27]. Further, close to one half of the nickel contained in new stainless steel is secondary [14, 26, 27]. Consequently, roughly 75% of the nickel used in automotive steel is secondary (R1 Nickel). We use a slightly lower number (70%) to account for fluctuations and potential losses to other nickel loops.
2. Estimated 60% on metal substrate and 40% on plastic substrate [26].

The recycling process for HEV NiMH batteries is open loop, no nickel from battery recycling is used to manufacture new batteries. Currently, nickel in HEV NiMH batteries is added to steel feedstock, or else a combination of mechanical and hydrometallurgical processes recover nickel and other metals [29]. Assuming a 98% recycling efficiency (further described in Section 2.3.2), recycling the NiMH batteries of the HEVs sold in 2004 represents approximately fourteen percent[5] of the nickel entering the R2 stream. NiMH HEV battery recycling contributes less than one percent of the nickel in the R3 stream with the 2004 HEV market share; thus a considerable increase in HEV usage is unlikely to significantly increase the amount of nickel released to the environment from the post-use phase.

[5] Assuming all 2004 HEVs reach their end of life in 2017 (after 13 years of use) and that nickel consumption has continued to grow at a rate of 4% per year.

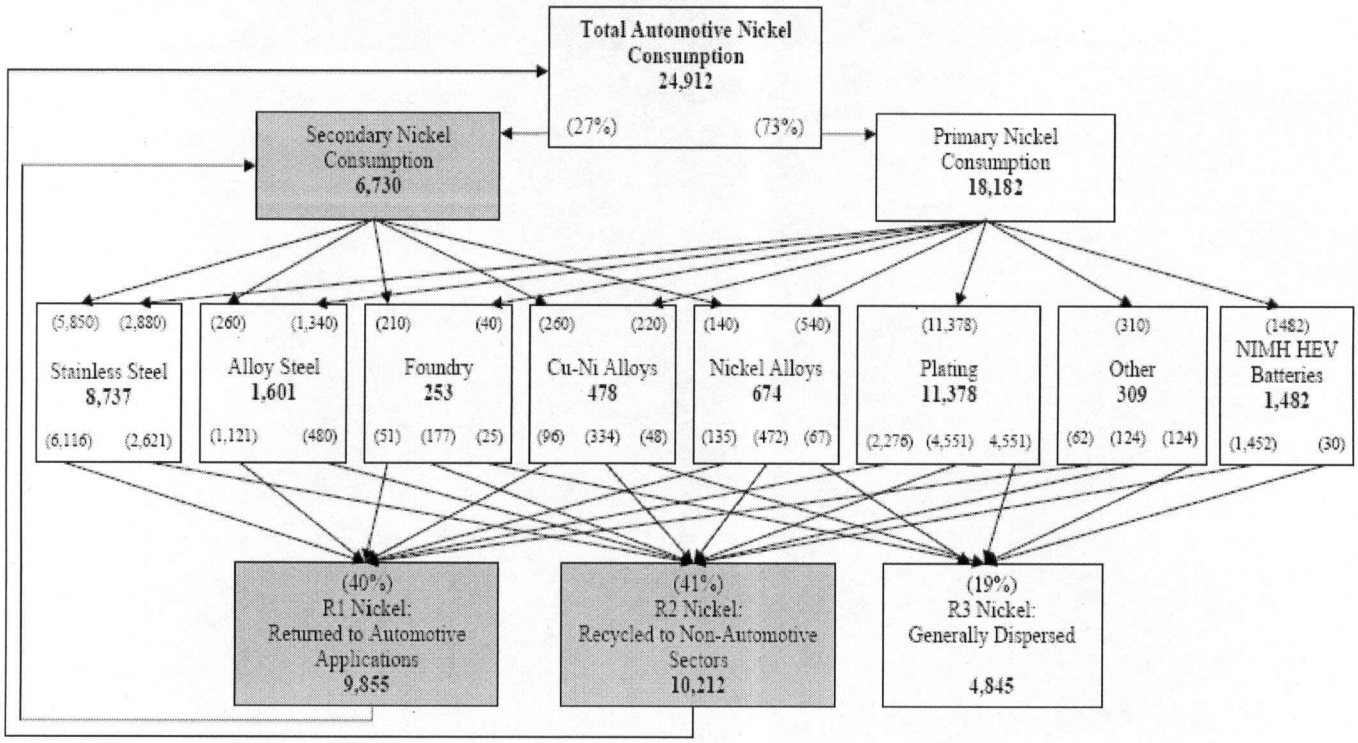


**Figure 2.2 2004 Flow of Nickel through North American Automotive Industry (in kilotons)**

Notes:

1. Sources: Consumption data: [10, 15] and expert interviews: [24,25,26,27].
2. Automotive totals include amount of nickel required for 2004 North American HEV market share.
3. Very few (if any) NiMH batteries are expected to have entered the nickel recycling and disposal system between 2000 and 2004.

## 2.3 NICKEL AND ASSOCIATED RELEASES FROM THE ICEV AND HEV LIFECYCLES

In this section, the nickel and associated toxic emissions released to the air from both mining and recycling of the nickel contained in automobiles are examined. The focus is on air emissions primarily because epidemiological evidence of health hazards points to exposures from air. In addition the following assumptions are made:

1. The burden of emissions associated with secondary nickel manufacturing is minimal [30]. Industry studies also show that minimal emissions result from the manufacturing of the battery from refined nickel [31]. The analysis therefore focuses on emissions from primary nickel production and battery recycling.

2. For analytical convenience it is assumed that the nickel used for HEV batteries is extracted and processed in North America.
3. A Toyota Prius represents the average HEV, while a Toyota Corolla represents a comparable ICEV. Both are assumed to weigh 1300 kg.
4. Each HEV uses one battery in its lifetime; the estimate would be revised upwards if the lifetime of an HEV battery turns out to be lower than expected.

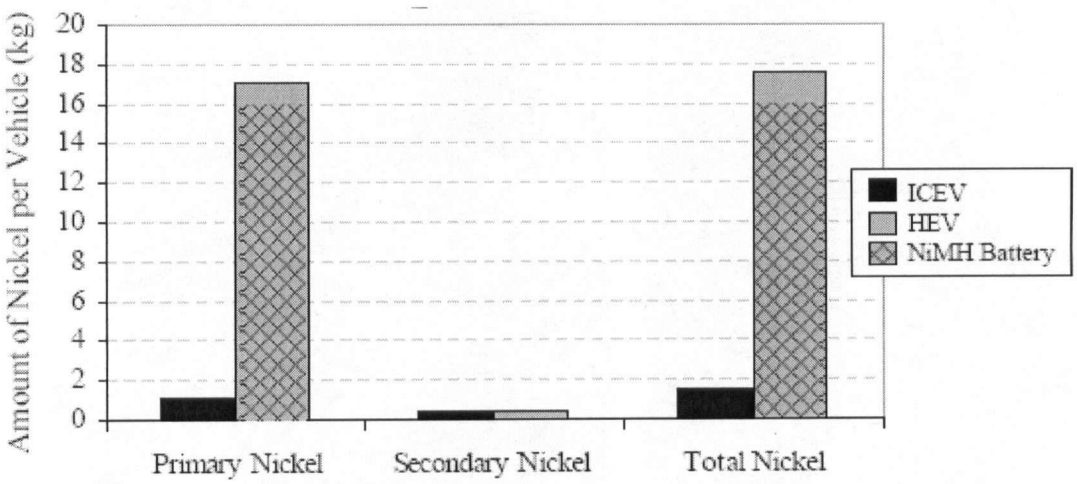


**Figure 2.3 Average Nickel Consumption per Vehicle (in kilograms)**

Notes:
1. Number of motor vehicles produced in N.A. in 2004 obtained from [36]; Assumes breakdown between primary and secondary inputs presented in Table 2 [9;10]; Amount Ni/NiMH battery for HEVs from [18]
2. Assumes all nickel contained in NiMH batteries mined in North America.

The total mass of primary and secondary nickel contained in a single automobile is presented in Figure 2.3. It is estimated that an average North American ICEV contains 1.6kg of nickel (1.14kg primary and 0.46kg secondary) and an average HEV of similar weight contains 17.6kg of nickel (17.14kg primary and 0.46kg secondary), which is an order-of-magnitude greater. The 'order-of-magnitude' ratio for the difference in nickel content between HEVs and ICEVs is roughly independent of the size of an automobile[6]. Further, the use of plated nickel in support cables, conductors, and electronics in HEVs may add up to an additional 6kg of nickel [35]. Unfortunately, such information is typically proprietary, uncertain, and difficult to verify hence not included in this analysis. However, this

[6] Increases in NiMH battery weight are proportional to increases in the weight of the HEV model [17]

uncertainty does not fundamentally alter the finding that the amount of nickel contained in an HEV is at least 10 times that in a conventional ICEV.

*2.3.1 Airborne Nickel Emissions in the Material Extraction Phase: Mining, Smelting, and Refining*

In what follows, the human health and environmental effects from the production of primary nickel for HEV NiMH batteries are described. Data from Canadian nickel mining and/or refining operations as well as environmental release data from Environment Canada's National Pollutant Release Inventory (NPRI) and the Nickel Institute, an industry-funded non-profit group, are used to estimate air releases from the metal extraction phase. In the following section, epidemiological studies based on worker exposures to nickel emissions in a Canadian setting are reviewed and the impact of these are assessed.

In the metal extraction phase, roughly 85% of airborne nickel emissions result from the smelting process, approximately 10-15% from refining, and very little from the mining phase itself [37, 38]. Total 2004 atmospheric nickel releases reported in the NPRI by each facility from two major Canadian nickel producers (Inco and Falconbridge) are calculated, along with estimates for total nickel production tonnage from these facilities. On average, Inco and Falconbridge facilities emit 1.1g of nickel to the air for each kilogram of finished nickel produced. The Nickel Institute Life Cycle Inventory Report calculates that 2.2g of nickel are released to the air for each kilogram of finished nickel produced in North America [38]. This gives a range of nickel emissions from 18-35g of nickel released during the metal extraction phase for every NiMH HEV battery produced. These emissions primarily affect the health of workers in refining facilities; the extent of potential occupational health impacts from HEV batteries is assessed below.

*2.3.1.1. Occupational Health Considerations*

In the North American occupational setting, worker exposure to a variety of nickel compounds depends upon the type of ore mined and the subsequent processing. Metallic, oxidic and sulfidic nickel, soluble nickel compounds, and nickel carbonyl are the primary forms of nickel to which workers can be exposed. Metallic and soluble nickels do not appear to be carcinogenic [39], while exposures to a mixture of sulfidic and oxidic nickel have been associated with small increases in respiratory cancers (of the nose, lung, and/or larynx) in human cohorts [39]. Small quantities of known and suspected respiratory carcinogens (nickel

aerosols, asbestos, sulphuric acid, cobalt, and arsenic) are also present in nickel smelters, refineries, and nickel mining environment [40][7].

The sintering operations of the Copper Cliff and Port Colbourne refineries (located in Ontario, Canada) exhibited exceptionally high airborne oxidic and sulfidic nickel concentrations prior to 1963 [39,43,46]. Workers in these facilities exhibited excess lung and nasal cancers. Both sintering plants have since been closed; Copper Cliff in 1963 and Port Colbourne in 1984. Measurements taken at the Copper Cliff smelter between 1988 and 1992 showed mean airborne nickel concentrations generally an order of magnitude lower than those associated with excess lung cancer risks[8][39]. Additionally, no excess laryngeal cancers have been observed among Canadian sinter workers [43,44,47].

Historically, very high concentrations (10mg/m$^3$ or higher) of sulfidic and oxidic nickel have been associated with increased risk of nasal and lung cancers in Canadian refining operations [39,48,49]. Current concentrations are smaller by at least one order of magnitude. Presently nickel exposures from mining, smelting, and refining are generally within enforced allowable occupational exposure levels [50], owing to vastly improved mitigation measures. In summary, there is some evidence that exposure to nickel in the metal extraction phase has historically lead to excess cancer risks among workers in North America. Due to improved standards and reduced exposures much of this risk has now been mitigated.

### *2.3.2 Automotive Nickel Releases in the Post-Use Phase: NiMH Battery Recycling*

HEV NiMH batteries are expensive and replacement costs have been estimated from $2K to $3K [51]. Further, manufacturers such as Toyota have instituted a $200 "bounty" program that encourages scrap dealers to remove NiMH batteries from HEVs and deliver them to a recycler [20]. Consequently, collection efficiency or the fraction of HEV batteries returned at the end of their functional lives is anticipated to be very high, i.e., close to 100%. The recovery rates of nickel in HEV NiMH batteries

[7] Canadian nickel mines extract nickel-sulfide ores [9]. However, more than two-thirds of the world's nickel reserves and resources are in tropical laterite ores (sulfide deposits make up the remainder) [41], future exploitation of which is thought will satisfy the growing demand for nickel [42]. Although one study found evidence of elevated levels of laryngeal cancer among (lateritic) nickel miners with extended exposure [43], no increase in nickel-related lung cancer risk has been observed [39,44]. Studies performed upon miners and smelters of lateritic nickel ores specifically [45] found no evidence of excess nickel-related respiratory cancer risks. A shift towards the increased production of nickel from lateritic ores will likely not present a serious escalation of cancer risks.

[8] Studies performed on refinery workers in Norway and Wales found that an excess of lung cancer was associated with long term exposure (15 years or more) to high concentrations (>=5mg/m3) of oxidic nickel and/or sulfidic nickel [39].

are not known; however data on household NiMH batteries is available. For such applications INMETCO, the major NiMH battery recycler in North America, achieves a 98% nickel recycling efficiency [22], using its pyrometallurgical high temperature metals recovery process. For the assumption of 16kg of nickel per HEV battery this results in 320g of additional nickel released to the environment.

Surprisingly, nickel releases of 18-35g from the metal extraction phase of a battery are lower than those estimated from the recycling phase. This result must be treated with caution; there is little experience with HEV recycling technology as few of the hybrid vehicles sold since 2000 have reached the end of their lives. Data on actual recycling efficiencies will emerge over the next few years as manufacturers scale up recycling facilities.

Here it is illustrative to compare the relative impacts of HEVs with those of EVs using LABs. Assuming 98% recycling efficiency for EV LABs and a mass of 325kg lead per battery [52], the amount of lead from released from recycling is 6.5kg compared with 0.32kg of nickel released per HEV NiMH lifecycle[9]. Lead is also the second entry on the US CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act) Priority List of Hazardous Substances for 2005, after arsenic and before mercury. Nickel is number 55 on this list of 275 hazardous materials [54], meaning it is less threatening to human health and the environment. Thus, NiMH batteries offer a total reduction in toxic metals being released to the environment when compared to LABs.

### *2.3.3 Environmental Emissions*

In addition to nickel emissions, the mining, smelting, and refining of primary nickel leads to a number of other pollutant releases. From the NPRI database [37] and data from the Nickel Institute [38], the mass of criteria air pollutants and other substantial atmospheric releases produced by the mining and refining of the primary nickel required for one HEV NiMH battery are calculated and tabulated in Table 2.4. In Table 2.4, these releases are further compared to emissions reductions achieved during the use-phase of the HEV over an equivalent ICEV. Emission factors of carbon monoxide (CO), nitrogen oxides ($NO_x$), non-methane hydrocarbons (HC), sulfur oxides ($SO_x$), and particulate matter

[9] Socolow and Thomas [52; 52a] (hereafter "ST") and Lave et al [53;53a;53b] (hereafter "LRHM") have debated the use of lead acid batteries. LRHM argued that the smelting and recycling of lead for LABs in EVs would cause more lead to be released per mile into the environment than an equivalent ICEV burning leaded gasoline. Consequently, environmental costs of zero-emissions vehicles that use a large quantity of lead could far exceed the local air quality improvements they may offer. ST countered that lead in batteries is not dissipative in the use-phase and maintained that clean recycling could minimize lead emissions from the use of EV batteries.

(PM) are taken from a previous study [55] and used to calculate HEV and equivalent ICEV use-phase fuel cycle emissions. Using two scenarios of vehicle usage, the fuel cycle emissions are added to tailpipe emissions released over the use-phase of these vehicles[10]. Table 2.4 quantifies the airborne emission savings and surpluses over the total lifecycle of the 2001 Toyota Prius as compared to the 2001 Toyota Corolla using scenarios of high and low usage in order to demonstrate the effect of mileage upon emissions benefits. The additional CO, $NO_x$, and HC emissions produced in the material extraction phase of the NiMH HEV battery are more than compensated for by reductions in the use-phase. Approximately 48 - 141kg of CO, 0.5 – 0.3kg of $NO_x$, and 2 – 6kg of HC are avoided during the lifecycle of an HEV as compared to an ICEV for low-and high lifetime mileage respectively. Such emissions reductions are possible because HEVs can de-couple the operation of the engine from the demands for road torque, offset the use of the internal combustion engine with the electric motor [6], and limit tailpipe emissions through specifically designed controls (discussed in more detail in Chapter 3).

Sulfur oxides ($SO_x$) are co-products from the smelting of sulfidic nickel ores. Approximately 20kg of $SO_x$ are emitted to the atmosphere for every NiMH HEV battery produced. The reduced fuel consumption does not compensate for the high levels of $SO_x$ emitted in the production of finished nickel. Consequently, HEV manufacture results in excess aggregate releases of SOx to the air over its lifecycle.

Historically, $SO_x$ emissions from nickel mining have been responsible for the acidification of proximal water bodies. In the Sudbury region of Canada, a major nickel producing region, $SO_x$ smelter emissions were deemed responsible for the acidification of local lakes as early as 1972 [57]. It is estimated that seven thousand lakes and nearby ecosystems in the Sudbury area were damaged [58]. Since 1980 $SO_x$ emissions from smelters have been reduced by more than 90% through better emissions control [59] and a slow ecosystem recovery is on its way [60]. Acid deposition in the region is now primarily a result of long-range transport and not local nickel smelters [60]. Therefore, though increased production of nickel for HEV batteries will increase $SO_x$ emissions, the impact of these emissions on local acidification is not likely to be significant.

[10] Comparison between a 2001 Toyota Prius and a 2001 Toyota Corolla is performed. Fuel consumption values for both vehicles are obtained from [56]. Methodology is described and further discussion is presented in Chapter 3.

**Table 2.4 Atmospheric Emissions Savings and Surpluses over Lifecycle of HEVs (kg)**

| | | Emissions Produced by Material Extraction Phase of HEV over ICEV[1] | Emissions Saved over Use-phase of HEV Lifecycle[2,3] | | Overall Savings/Surpluses of Emissions over HEV Lifecycle[4] | |
|---|---|---|---|---|---|---|
| | | | Low km | High km | Low km | High km |
| Criteria Air Pollutants | CO | 0.62 | 49.10 | 142.39 | 48.48 | 141.77 |
| | NOx | 0.74 | 1.11 | 0.95 | 0.37 | 0.20 |
| | HC | 0.21 | 2.00 | 5.96 | 1.79 | 5.75 |
| | SOx | 17.79 | 0.07 | 0.23 | -17.72 | -17.56 |
| | PM | 0.58 | 0.02 | 0.08 | -0.56 | -0.51 |
| | $NH_3$ | 0.091 | | | -0.091 | -0.091 |
| | Cu | 0.008 | | | -0.008 | -0.008 |
| | As | 0.006 | | | -0.006 | -0.006 |
| | Pb | 0.004 | | | -0.004 | -0.004 |

Notes:

CO - carbon monoxide; $NO_x$ - oxides of nitrogen; HC – non-methane hydrocarbons; $SO_x$ - oxides of sulfur; PM - particulate matter; $NH_3$ – ammonia; Cu - copper; As - arsenic; and Pb - lead.

1. Emissions produced by the mining and refining of primary nickel for the HEV NiMH battery. Masses represent the average of values obtained from [37] and [38]. Amount of primary nickel contained in an HEV NiMH battery is 16kg as per [18].
2. Emissions savings methodology described in Chapter 3. Use-phase emissions savings represent tailpipe and fuel cycle emissions with emission factors obtained from [55].
3. High km scenario represents vehicle lifetime mileage of 500,000 miles and low km scenario represents vehicle lifetime mileage of 145,300 miles.
4. Difference between previous two columns. Negative values represent emissions surpluses over the HEV lifecycle.

## 2.4 CONCLUSIONS

HEVs contain the same amount of recycled nickel as conventional vehicles, but 15 times the amount of primary nickel. The diffusion of HEV technology over time will therefore have a substantial impact on future material flows of nickel in the North American economy. The human health effects of excess nickel releases from these flows are likely to be small. Furthermore, airborne emissions of criteria pollutants from HEV battery production are dominated by air quality improvements during the use phase. Although SOx emissions from the material extraction phase are not fully compensated for in either usage scenario, in general more miles traveled in the HEV translates into more emissions savings as compared to an equivalent ICEV. These findings coupled with the substantial fuel consumption reductions from HEVs provide a more complete picture of their environmental benefits.

## 2.5 ACKNOWLEDGEMENTS

This research was funded by the Auto-21 Network Canada. We would like to thank the following experts for their time: Bill McCutcheon, Natural Resources Canada; Gary Coates, Nickel Institute; Barry Waters, Nickel Institute; Damien D'Aquiar, Inco Nickel; Linda Wing, Enthone. The usual disclaimers apply.

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# CHAPTER 3: AN ENVIRONMENTAL EVALUATION OF THE USE-PHASE OF HYBRID-ELECTRIC VEHICLES: THE TOYOTA PRIUS FROM THE REGULATORY AND IN-USE PERSPECTIVES

**NOTE:**

A version of this paper will be submitted for publication. Jones, K., Kandlikar, M. An Environmental Evaluation of the Use-Phase of Hybrid-Electric Vehicles: The Toyota Prius from the Regulatory and In-Use Perspectives, Transportation Research Part D. Submission to journal pending.

## 3.0 INTRODUCTION

Hybrid-electric vehicles (HEV) are a proven means to reduce fuel consumption and lower greenhouse gases compared to an equivalent conventional internal combustion engine vehicle (ICEV) [1,2]. Such benefits come from the use of a smaller, more efficient ICE, an electric motor that either enhances or substitutes the gasoline-powered torque of the ICE at certain times of the drive cycle, and regenerative braking that captures dissipative energy. In addition to reduced fuel consumption, HEVs use advanced controls to lower emissions of other tailpipe pollutants. Currently, the best selling HEV on the North American market is the Toyota Prius, representing more than 40% of the over 250,000 HEVs sold in the US in 2006 [3].

The objective of this paper is to compare the use-phase emissions of an HEV and an equivalent conventional ICEV over their respective lifetimes and to quantify the air emissions benefits offered by the HEV model. There has been substantial work done in comparing fuel economy and $CO_2$ benefits of HEVs vs. ICEVs [4,5]. However, despite claims by manufacturers that HEVs are clean and low polluting vehicles, there are no studies examining their in-use lifecycle air quality benefits. In this work, tailpipe and fuel cycle emissions of three criteria pollutants are compared - carbon monoxide (CO), oxides of nitrogen ($NO_x$), and non-methane hydrocarbons (HC)[11] - for the Model Year (MY) 2001 Toyota Prius, with those from MY 2001 Toyota Corolla, Toyota Echo, and Honda Civic. These vehicles are chosen because they are of the same size class, similar in passenger and luggage capacities and engine size, and have been compared in previous studies [4].

[11] Differences in particulate matter emissions between HEVs and ICEVs are anticipated to be similar given that LEV, ULEV, and SULEV emission standards for this pollutant are the same.

A direct quantification of the total use-phase emissions reductions offered by the useful life of a MY 2001 Prius over the Corolla, both of which are classified as compact cars and previously compared in analyses [4 and 5], is also performed. To make this comparison possible two independent sets of data are used:

(i) **Regulatory Data Set**: Emission factors and fuel economy values provided by regulatory agencies and vehicle manufacturers are used. The United States Environmental Protection Agency (EPA) measures emissions factors and fuel consumption of new light duty vehicles using the Federal Test Procedure (FTP) which attempts to reflect actual driving conditions encountered in the use phase [6]. The emission factors derived from these tests apply to new vehicles and not to vehicles in the operating fleet.

(ii) **In-Use Testing Data Set**: In-use vehicle emissions testing results are used. Inspection and Maintenance (I/M) emissions testing programs, such as the AirCare program in the City of Vancouver and the Lower Fraser Valley (LFV), use a variety of in-use test procedures, one being the IM240 test - a variant of the FTP, to identify high-emitting in-use vehicles.

Though there are known discrepancies between performance characteristics estimated by such test procedures and those demonstrated in real-world driving conditions [7], these tests provide the best available information on actual emissions from vehicles. The rest of the paper is structured as follows. In section 3.1, the methods used in evaluating lifetime use-phase emissions of criteria air pollutants (3.1.1 for tailpipe emissions and 3.1.2 for fuel cycle emissions) of the HEV and ICEVs are outlined. In section 3.2, results on estimates of lifecycle emissions for the Prius versus the Corolla are presented. Conclusions in section 3.3 are followed by a discussion focusing on the observed differences between HEVs and ICEVs emissions data as evidenced in the regulatory vs. in-use testing data.

## 3.1 METHOD

Use-phase emissions in a vehicle lifecycle are large compared to those resulting from vehicle manufacture and end-of-life recycling and/or disposal [8]. Consequently, a focus on the use-phase emissions captures a significant portion (> 75%) of all lifecycle emissions [9]. Use-phase emissions in this analysis are calculated using the formula:

$$Etot_{(i,j)} = Efac_{(i,j)} * M \qquad (1)$$

where the M is the lifetime mileage. It is further assumed that all emission factors $Efac_{(i,j)}$ for the $i^{th}$ pollutant are maintained over the useful life of the vehicle type j.

*3.1.1 Criteria Air Pollutant Emissions*

**In-Use Estimates of Emissions Factors:** Tailpipe emissions testing data is obtained from AirCare, the vehicle emissions I/M testing program for Vancouver and the LFV in British Columbia, and is used to derive in-use emissions factors. The purpose of the AirCare program is to address the ground level ozone problem in the LFV. It identifies vehicles with high tailpipe emissions and mandates emissions control system repairs when required; thereby reducing automobile-generated emissions. At the time of testing, the vehicles in the dataset were required to undergo the IM240 test, a drive cycle consisting of a pre-defined series of accelerations, decelerations, and cruise conditions (the average speed of the cycle is 48 km/hr and the maximum speed attained is 92 km/hr, covering a distance of approximately 3.2 km) conducted on a chassis dynamometer, over a total duration of 240 seconds. Only vehicles that completed the full IM240 emission test (no "fast pass" results) are included in the dataset. Data points are checked against the AirCare Centre location and lane at which the vehicles were tested in order to eliminate faulty equipment or sampling biases. No systematic biases are detected.

**Regulatory Certification Estimates of Emissions Factors:** The certification of new vehicles to federal emission standards is achieved by performing the FTP on a chassis dynamometer with pre-production vehicles. Vehicle emissions from certification testing are by definition lower than the emission standards to which the vehicle is regulated. EPA audits data from such testing performed by vehicle manufacturers at their respective facilities as well as confirms some of the results by performing its own testing [11]. Throughout this paper, the in-use emission factor estimates are compared with the emission factor estimates from certification test results provided by the EPA in its Annual Certification Test Results Report. The certification testing results represent emission factors to be expected from standard versions of these vehicles [12] that would be driven on the roads and subsequently tested in I/M programs such as AirCare.

The FTP is characterized by three main components – a cold-start phase at the beginning, followed by a hot stabilized phase, and finally a hot-start phase at the end. Supplemental procedures including a high acceleration cycle and an air conditioning cycle are also used to further mimic real-world conditions.

The IM240 cycle is a transient test conducted upon a chassis dynamometer that is derived from the FTP, and closely mimics its hot-start phase in terms of vehicle operating temperature, speed, acceleration, and deceleration. Of all I/M programs, the IM240 correlates most closely with the FTP [14], however as mentioned it is conducted under hot-start conditions only and has no cold-start or stabilized operation component.

### *3.1.2 Emissions from Gasoline Production*

The emissions "upstream" of the vehicle include those resulting from crude oil extraction through fuel distribution [14] and are assumed to be proportional to the amount of fuel used. Regulatory and in-use fuel economy values for the Toyota Prius, Corolla, Echo, and Honda Civic are provided in Appendix A and are used to estimate lifetime fuel consumption and subsequent use-phase emissions of CO, HC, and $NO_x$ using fuel cycle emissions factors from a previous study by Lave and Maclean [8]. Fuel cycle emission factors and lifetime fuel cycle emissions for all vehicles are presented in Table 3.2 in terms of two scenarios of lifetime usage; high mileage (500,000 miles) and average mileage (145,300 miles) as per [10].

## 3.2 RESULTS

### *3.2.1 Criteria Air Pollutants*

Table 3.1 lists the mean value and standard deviation of emission factors of CO, HC, and $NO_x$ for the entire population of in-use Prius vehicles tested in Vancouver between 2001 and 2004 (n = 227) and a random selection of MY2001 ICEVs (44 Corollas, 17 Echos, and 94 Civics).

**Table 3.1 AirCare Dataset Details and Criteria Pollutant Emission Factors**

| Vehicle | Model Year | n | Avg Odometer (000 km) | Avg Age (years) | CO (g/km) | | HC (g/km) | | NOx (g/km) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $\mu_A$ | $\sigma_A$ | $\mu_A$ | $\sigma_A$ | $\mu_A$ | $\sigma_A$ |
| Toyota Prius | 2001 | 227 | 47.73 | 3.26 | 0.65 | 0.56 | 0.028 | 0.037 | 0.011 | 0.012 |
| Toyota Corolla | 2001 | 44 | 50.84 | 3.26 | 0.53* | 0.61 | 0.038$^+$ | 0.034 | 0.12$^+$ | 0.087 |
| Toyota Echo | 2001 | 17 | 50.53 | 2.84 | 0.31 | 0.35 | 0.038 | 0.023 | 0.15 | 0.080 |
| Honda Civic | 2001 | 94 | 52.35 | 3.58 | 0.35 | 0.40 | 0.013 | 0.019 | 0.044 | 0.035 |

CO – carbon monoxide; HC – non-methane hydrocarbons; $NO_x$ – oxides of nitrogen.
$\mu$ - average emission factor; $\sigma$ – standard deviation of emission factor.
* Indicates difference between Corolla and Prius statistically significant at the 90% level or higher.
$^+$ Indicates difference between Corolla and Prius statistically significant at the 95% level or higher.
Differences between ICEV and HEV results for all pollutants are outside the range of emission measurement equipment error.
Average age represents number of years vehicle has been in service since the date of sale (assumed to be January 1, 2001 for all vehicles) to the date of emission testing. There is no significant correlation between age or mileage with emissions of any criteria pollutant.

Figures 3.1, 3.2, and 3.3 show the cumulative distribution of Prius and ICEV AirCare emissions testing results for CO, HC, and $NO_x$ respectively. Lifetime use-phase emissions calculated using the average in-use emission factors ($\mu_A$) for the Prius and Corolla in g/km using Equation 1 are compared in Table 3.3 for each pollutant according to the regulatory and in-use estimates respectively.

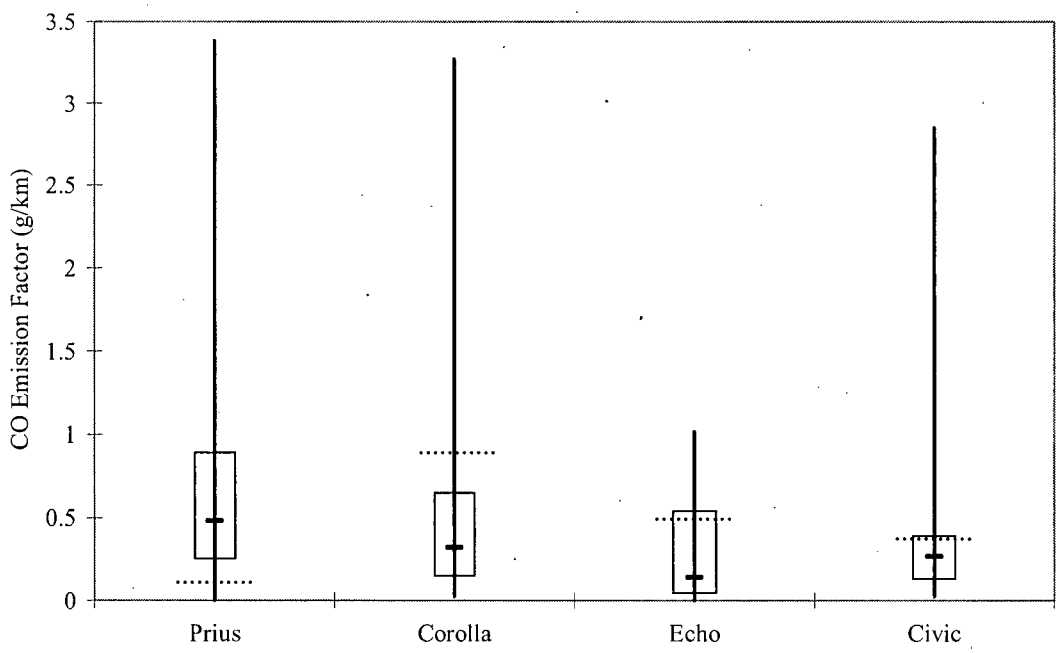


**Figure 3.1 AirCare IM240 Carbon Monoxide (CO) Emissions Testing Results for MY2001 Vehicles**

Notes:
Dotted lines denote EPA FTP Certification test result for vehicle.
Dash represents statistical median of dataset.
Prius and Civic federally certified to ULEV standard; Corolla and Echo federally certified to LEV standard.
Cumulative distribution diagrams for this information can be found in Appendix A.

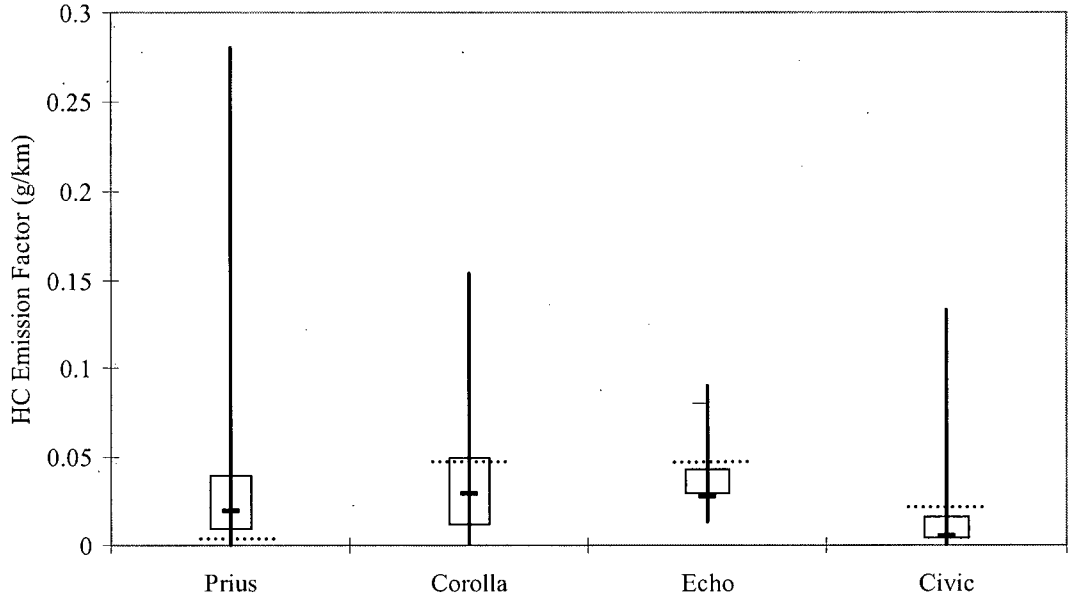


**Figure 3.2 AirCare IM240 Hydrocarbon (HC) Emissions Testing Results for MY2001 Vehicles**

Notes:
See notes from Figure 3.1.

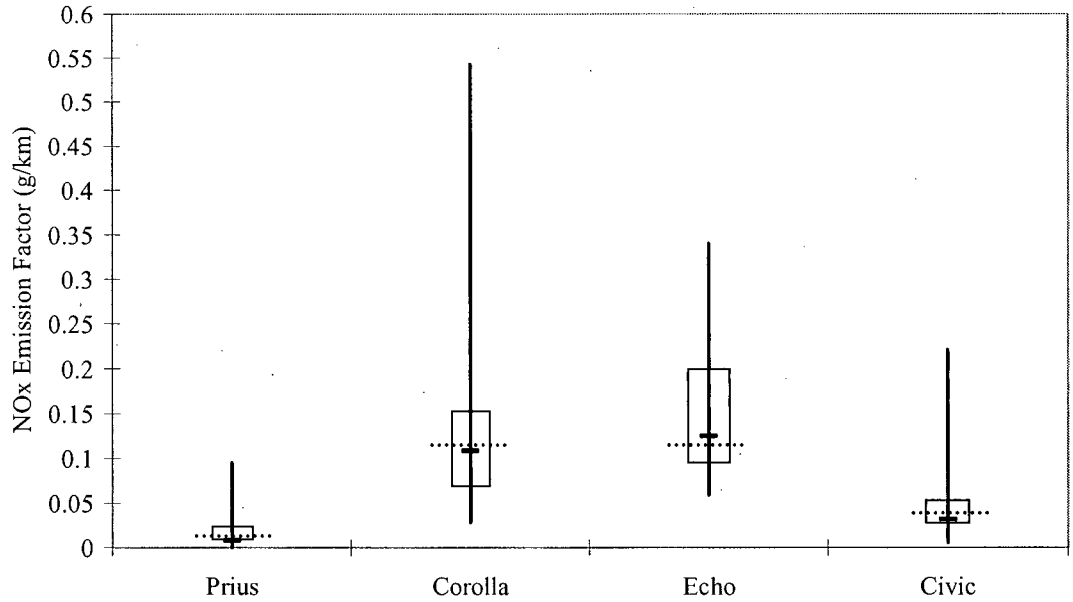


**Figure 3.3 AirCare IM240 Oxides of Nitrogen ($NO_x$) Emissions Testing Results for MY2001 Vehicles**

Notes:
See notes from Figure 3.1.

In general, emissions from the IM240 test for the average in-use Corolla are below the level to which the vehicle is certified and vice versa for the average in-use Prius. As shown in Figures 3.1 and 3.2, emissions from 89% and 95% of the in-use Priuses *exceed* the EPA certification level for CO and HC respectively, whereas this proportion is much smaller for in-use Corollas (only 10% and 27% respectively). The difference between the in-use and regulatory emissions estimates for the Prius and Corolla is less stark for $NO_x$. About 58% and 48% respectively exceed the EPA certification test result for $NO_x$ (Figure 3.3).

What explains the unexpectedly-high in-use Prius emissions vis-à-vis EPA certified emission factors? First, the FTP cycle is used to establish specific certification level emissions whereas the IM240 test aims to identify vehicles with abnormally high emissions [15]. Second, HEVs may be less compatible with standard tailpipe test procedures like the IM240[12] than ICEVs. Three reasons why this is most likely the case are identified: the absence of a cold start test phase, lack of preconditioning[13], and lack of battery state of charge controls[14] in the AirCare procedure.

Data from emissions testing of individual stages of the FTP show that the cold-start phase is the single largest contributor to FTP emissions for both HEVs and ICEVs [16]. However, the Prius employs unique controls specific to reducing cold-start emissions and warming up the catalytic converter as quickly as possible. Santini et al, (1999) [16] found that the ratios of cold-start to hot-start phase emissions are 5.5/2/2 times higher for ICEVs than HEVs[15] for CO/HC/$NO_x$ respectively in the FTP. Since cold-starts make a larger contribution to in-use emissions in ICEVs relative to HEVs, the absence of a cold-start phase in the IM240 cycle penalizes HEV emissions. During the hot-start phase of vehicle operation, the IM240 and FTP procedure mimic each other well [16], suggesting that the primary difference between in-use IM240 testing results and FTP data is due to the absence of the cold-start and stabilized test phase. The other differences in HEVs and ICEVs vis-à-vis testing - lack of preconditioning, and lack of battery state of charge controls are likely to have an impact on differences

[12] Recently, EPA has exempted them from in-use exhaust emissions testing, upon the specific provision of the Code of Federal Regulations 40 CFR 86.1427(d) [6].

[13] The IM240 is conducted without standard preconditioning procedures, thus vehicles enter the test at varying levels of catalyst and engine warmth. This may lead to different results for HEVs.

[14] During testing waits HEV battery state of charge decreases, which in turn is associated with more engine starts/stops [18]. Although stopping the engine conserves fuel, hot starts are made smooth by over-fueling, causing bursts in HC emissions that can reach higher than a few thousand ppm [17].

[15] Study compares the average emissions in the FTP Bag 1 (cold-start), Bag 2 (stabilized), and Bag 3 (hot-start) and the total weighted cycle emissions for three MY 1998 ICEVs with a first generation Toyota Prius.

between emissions from the two types of vehicles; however the weighting of vehicle operation phases is concentrated upon in this study.

*3.2.2 Emissions from Gasoline Production*

EPA certified fuel economy data for HEVs are known to be overestimates [5]. Therefore, for calculating gasoline consumption during vehicle lifetime, "Your MPG"[16] values based on user feedback fuel economies are used. These values amount to 88% and 97% of the EPA FTP fuel economies for the Prius and Corolla respectively. Using emission factors shown in Table 3.2, fuel cycle emissions over the use-phase of the Prius are calculated to be 5.25kg for CO, 2.58kg for HC, and less than 1kg for $NO_x$ for the average mileage scenario; a reduction of 33% over the Corolla. In addition, fuel cycle calculations for PM and $SO_x$ also demonstrate the same 33% reduction for the Prius over the Corolla. Over higher lifetime vehicle mileage, the same proportion of fuel cycle emissions is saved, although the total masses are larger.

**Table 3.2 Lifetime Fuel Cycle Emissions of MY2001 Vehicles (kg)**

| | Criteria Air Pollutant | | | | | |
|---|---|---|---|---|---|---|
| | CO | | HC | | $NO_x$ | |
| Emission factor (g/km) | 0.44 | | 0.22 | | 0.061 | |
| *Mileage Scenario* | *High* | *Average* | *High* | *Average* | *High* | *Average* |
| Toyota Prius | 18.07 | 5.25 | 8.89 | 2.58 | 2.49 | 0.72 |
| Toyota Corolla | 27.13 | 7.89 | 13.35 | 3.88 | 3.73 | 1.09 |
| Toyota Echo | 23.69 | 6.88 | 11.66 | 3.39 | 3.26 | 0.95 |
| Honda Civic | 24.44 | 7.10 | 12.03 | 3.50 | 3.36 | 0.98 |

Notes:
CO – carbon monoxide; HC – non-methane hydrocarbons; $NO_x$ – oxides of nitrogen;
Emission factors for gasoline fuel cycle obtained from MacLean & Lave, 1998 [8].
In-use fuel economy estimates based on "Your MPG" values as provided by EPA.
High mileage defined as useful miles equal to 500,000 and low mileage defined as useful miles equal to 145,300 miles [10].

## 3.3 LIFE CYCLE EMISSIONS OF PRIUS VERSUS COROLLA

Due to improved fuel economy, the Prius has lower *fuel cycle emissions* throughout its useful life by 2kg of CO, 1kg of HC, 0.3kg of $NO_x$, and small amounts of SOx and PM (over average lifetime

[16] Created by the U.S. Department of Energy and the U.S. EPA, "Your MPG" (www.fueleconomy.gov/mpg/MPG.do) is a website that enables drivers to calculate and track their fuel economy and compare it with EPA test ratings or share it with other users.

mileage) as compared to its equivalent conventional ICEV, the Corolla. In other words, Prius emissions for the fuel cycle portion are 27-33% lower. However, as shown below tailpipe emissions from fuel use are an order of magnitude (or more) higher than emissions released in the production of fuel.

In order to evaluate more realistic emissions factors than specified by the IM240 test, three scenarios of cold-/hot-start weighting over the complete drive cycle are developed – a base case, a high cold-start scenario where every start is modeled as a cold-start, and a low cold-start scenario where only one start per day (the morning start) is modeled as a cold-start. These scenarios are applied to two different levels of vehicle usage and used to calculate the percentage of vehicles miles traveled (VMT) in the cold-start mode, resulting in a total of six scenarios. This alters Equation 1 in the following way:

$$Etot_{(i,j)} = M * (EfacCS_{(i,j)} * \%VMT_{cold} + EfacHS_{(i,j)} * \%VMT_{hot} + EfacS_{(i,j)} * \%VMT_{stab}) \quad (2)$$

where $Etot_{(i,j)}$ = Total emissions of $i^{th}$ pollutant over the lifecycle of vehicle type j

$M$ = Lifetime mileage

$EfacCS_{(i,j)}$ = Cold-start phase emission factor for the $i^{th}$ pollutant and vehicle type j

$\%VMT_{cold}$ = Percent of VMT in cold-start operation

$EfacHS_{(i,j)}$ = Hot-start phase emission factor for the $i^{th}$ pollutant and vehicle type j

$\%VMT_{hot}$ = Percent of VMT in hot-start operation

$EfacS_{(i,j)}$ = Stabilized phase emission factor for the $i^{th}$ pollutant and vehicle type j

$\%VMT_{stab}$ = Percent of VMT in stabilized operation

The high mileage scenarios are meant to represent taxi drivers that cover more miles and perform more engine stops per day than the average driver. Emissions factors for the cold-start and stabilized phase are based on Santini et al. [16] and are combined with hot-start IM240 test data to calculate total tailpipe emissions over vehicle lifetime.

**Scenario 1 – Base Case**: For the base case 43% of all vehicle starts are assumed to occur with cold engines (and therefore cold catalysts) based on EPA data [18]. Based on data from the 2001 National Household Travel Survey [20], it is further calculated that 4.4% of VMT are driven in cold-start

operation[17], 5.9% of VMT are driven in hot-start operation, and 89.7% of VMT are driven in stabilized operation. Vehicles for this and the following two scenarios are driven 145,300 miles over their useful lives.

**Scenario 2 – High Cold Start Scenario:** Here all vehicle starts done during the day are assumed to be cold-starts, this translates into 10.2%, 0%, and 89.8% of all VMT being driven in the cold-start, hot-start, and stabilized modes respectively.

**Scenario 3- Low Cold Start Scenario:** Here each vehicle is assumed to make only one cold-start per day in the morning. This translates into 2.5%, 7.8%, and 89.8% of all VMT being driven in the cold-start, hot-start, and stabilized modes respectively.

**Scenario 4 – Base Case with High Mileage:** As in Scenario 1, 43% of starts are cold-starts. However using the assumption of lifetime mileage of 500,000 miles, this corresponds to 2.7%, 3.6%, and 93.7% of VMT being driven in cold-start, hot-start, and stabilized modes respectively.

**Scenario 5 – High Cold Start with High Mileage:** As in Scenario 2, all vehicle starts are assumed to be cold starts. This corresponds to 6.4%, 0%, and 93.6% of all VMT being driven in the cold-start, hot-start, and stabilized modes respectively.

**Scenario 6 – Low Cold Start with High Mileage:** As in Scenario 3, one vehicle start per day is a cold-start. This corresponds to 0.6%, 5.7%, and 93.6% of VMT driven in cold-start, hot-start, and stabilized modes respectively.

[17] Calculated using the following values: Driving time required to warm from cold operation = 2 minutes [19]; average speed of vehicle travel on all roadways = 26.7 mph [20]; vehicle starts/day = 4 [21]; and distance traveled per day per vehicle = 35.49 miles [21]. For scenarios 4-6, daily travel is assumed to be 140 miles and vehicle starts per day is assumed to be increased to 10.

**Table 3.3 Differences (A-B) in Lifetime Tailpipe Emissions of 2001 Toyota Corolla (A) and 2001 Toyota Prius (B)**

| Use-Phase Emissions Scenario | CO | | HC | | NOx | |
|---|---|---|---|---|---|---|
| | kg | % diff | kg | % diff | kg | % diff |
| EPA Certification Result (low lifetime mileage) | 176.7 | 85.4 | 10.1 | 96.7 | 24.7 | 94.4 |
| EPA Certification Result (high lifetime mileage) | 608.0 | 85.4 | 34.8 | 96.7 | 85.0 | 94.4 |
| Scenario 1 | 46.5 | 57.2 | 0.7 | 19.1 | 0.8 | 10.6 |
| Scenario 2 | 80.5 | 70.1 | 1.3 | 23.8 | -0.1 | -1.6 |
| Scenario 3 | 35.2 | 50.2 | 0.5 | 16.3 | 1.0 | 14.7 |
| Scenario 4 | 133.3 | 56.5 | 1.5 | 15.4 | -0.3 | -1.5 |
| Scenario 5 | 206.7 | 67.0 | 2.9 | 20.6 | -2.1 | -10.0 |
| Scenario 6 | 91.0 | 46.9 | 0.7 | 9.7 | 0.8 | 3.7 |

Notes:
% diff denotes difference in lifetime emissions of Prius and Corolla as a fraction of emissions from the Corolla.

As shown in Table 3.3, the in-use HEV emission reductions for all scenarios are smaller that those based on EPA emission factors. It is observed that with a higher percentage of VMT traveled in cold operation (Scenarios 2 and 5), a higher percentage of CO reductions are achieved. However over a longer total lifetime distance with longer daily trips, a smaller percentage of miles are spent in the cold-start mode, thus there is actually a smaller emissions reduction benefit. CO emission reductions range from approximately 50% to 70% for both high and low mileage situations. With higher mileage, emissions of HC are slightly higher in mass and emissions reductions are slightly lower in percentage, but still ranging from an improvement of 10% to 23%. The Pruis does not seem to offer significant benefits in $NO_x$ emissions when more VMT are spent in the stabilized phase. Prius $NO_x$ emissions range from 15% less to 10% more than the Corolla over the six lifetime scenarios. According to [16], the CO emissions of the Prius in the stabilized phase are half that of the Corolla whereas $NO_x$ emissions are slightly higher. Being that in the scenarios vehicles travel a large proportion of their distance in the stabilized mode, this could explain the elevated $NO_x$ emissions.

## 3.4 DISCUSSION AND CONCLUSIONS

Emissions reductions require efficient combustion, a catalytic converter warmed to its optimal operating temperature, and an optimal air-to-fuel mixture. Lower tailpipe emissions are expected from the 2001 Toyota Prius relative to the Corolla for three specific reasons: the engine is operated at a stoichiometric air-fuel ratio for all power-demand conditions [1]; the start-stop nature of the HEV

prevents engine idling and keeps the catalytic converter close to optimal temperature [21]; and the use of a hot coolant upon start-up helps limit the release of cold-start emissions [22].

There is a discrepancy in all pollutant emissions between the regulatory certification and in-use test data for HEVs. Incorporating cold-start emissions into in-use test data partially reconciles these differences however it is evident there is a fundamental disconnect between the cold-/hot-start weighting for HEVs and ICEVs in the test procedures. The cold-/hot-start weighting applied in the FTP aims to characterize a single mode of operation under two different initial conditions in order to obtain an aggregated average emissions rate over a given distance [23]. Given the presence of specific controls to reduce time spent in the cold-start mode and the start/stop nature of the HEV causing more hot-starts over a given distance, there is justification in stating that there are alternative possibilities to the cold-/hot-start weighting of HEV characterization.

Incorporating cold-start emissions into in-use IM240 test data demonstrates that with more cold-starts, the Prius reduces proportionally more CO over the Corolla. However, with higher lifetime mileage and longer trip length, there seems to be a slight decrease in the proportion of HC and $NO_x$ emission reductions offered by the Prius over the Corolla. In stabilized operation, emissions from the Prius are higher for NOx and equal for HC relative to the Corolla. Over longer trips a lower proportion of vehicle miles are traveled in cold operation, actually resulting in an emissions detriment in $NO_x$, a pollutant with respiratory impacts on human health and acidification effects on ecosystems. Verifying the stabilized emission factors of the Prius would be a valuable addition to this study, although beyond its scope. It can be stated however, that the scenarios with the highest (Scenario 3) and lowest (Scenario 5) proportion of hot-start VMT are characterized by the largest improvement and detriment respectively in NOx emissions. Thus, with improved characterization of the cold-/hot-start weighting of HEVs, more substantial NOx emissions reductions may eventually be seen.

Although the Prius provides emissions benefits as compared to the Corolla over the use phase of its lifecycle, most of the improvements are gained when the vehicle is operating in cold-start mode, most notably in CO emissions. Exceedences of CO (during winter inversions and otherwise) have been decreasing since the mid-1990s in any case due to controls such as lower vehicle emissions and the use of oxygenated fuels [24]. Further, despite the Prius' improvement in NOx and HC emissions, the effect that reductions of these two pollutants will have on the frequency of ozone pollution events is difficult to quantify. Ozone concentrations vary geographically, seasonally, and daily as a function of complex

reactions between NOx and HC emissions. Being that vehicle emissions in general are continually improving, the emphasis of HEVs towards addressing emissions of the highest polluting phase of the drive cycle, the cold start, is an effective means to reduce tailpipe emissions.

## 3.5 ACKNOWLEDGEMENTS

Thanks to Stephen Stewart, Dave Gourley, and Jimmy Wong of Translink for the generous provision of AirCare emissions data and Jim Vanderwal of the Fraser Basin Council for the government fleet fuel economy data. Technical guidance provided by Conor Reynolds, Hadi Dowlatabadi, and Steve Rogak of UBC. Financial assistance provided by Auto21 Networks of Excellence.

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# CHAPTER 4: CONCLUDING CHAPTER

## 4.0 CONCLUSION

Manuscript 1 details the excess nickel and associated emissions that are released throughout the lifecycle of an HEV in addition to those that are released by an equivalent ICEV. Manuscript 2 quantifies the tailpipe emission reductions HEVs achieve over their ICEV equivalents in the use-phase. In section 1.8 of this thesis, it is hypothesized that the local environmental benefits of HEVs outweigh the environmental effects of transferred pollutants outside of its use-phase. Using the conclusions of these two manuscripts, a complete inventory of the HEV lifecycle in terms of air pollutant emissions can be compared to that of an equivalent ICEV; and an informed evaluation of local emission improvements versus total pollutant transfers can therefore be performed. However the overall environmental performance of the HEV cannot be gauged until an understanding of the impact of these emissions and emission reductions is obtained. As described in Section 4.1, a life cycle impact assessment (LCIA) functions to improve the understanding of the information gathered in the inventory phase of the life cycle assessment (LCA) [1] in order to weigh the overall impact of a pollution source. The overall impact of the average HEV lifecycle as compared to an equivalent conventional ICEV is then evaluated in Section 4.2. Sections 4.3, 4.4, and 4.5 consider the strengths and weaknesses of the research and assess the value of the findings.

## 4.1 LIFECYCLE ASSESSEMENT TO LIFECYCLE IMPACT ASSESSMENT

The HEV and the ICEV are characterized by different levels of performance with respect to different pollutants and stages of vehicle life making the overall impact of each respective vehicle lifecycle different. In order to examine whether the total environmental impact of the HEV lifecycle is outweighed by the improvements it offers over the ICEV in the use-phase, a decision making process that can account for multiple criteria is called for. For the purpose of this thesis, the concept of intake fraction is used to evaluate and compare the overall impact of the HEV and ICEV lifecycles.

### *4.1.1 Weaknesses of Lifecycle Assessment*

Two main weaknesses exist within the methodology and outcome of the LCA conducted in this thesis that have implications upon the ability to apply the results towards an interpretation of impact upon environmental or human health:

(1) Spatial considerations are not emphasized beyond the understanding that nickel and associated nickel mining emissions occur at the nickel mining site and tailpipe emissions occur on the road.

(2) Temporal considerations, such as the release of tailpipe pollutants over the lifetime of the vehicle versus nickel emissions occurring essentially at a point in time, are not considered.

Aggregating quantities without considering temporal or spatial traits can lead to an inaccurate and unrepresentative understanding of the actual impact of the system in question. Without the ability to understand exposure, estimate ambient concentrations, or account for applicable influences and interactions, an LCA cannot gauge distinct effects [1,2].

### *4.1.2 The Role of the Impact Assessment*

Data from the inventory phase of an LCA can be used to profile the overall environmental burden of a system; an impact assessment uses inventory data pertinent to a specific product system to examine the potential influence it may have on the environment [2]. Where Chapters 2 and 3 of this thesis quantify emission releases over the lifecycle of an HEV as compared to an ICEV, no interpretation of actual environmental effects is carried out. Impact assessments are simplifications [2] which serve to inform upon the direction or trend of a given measurement in the context of its effect on the environment.

The concept of "intake fraction" stems from the idea that all sources of pollution are not equal in terms of human exposure. Simply put, determining the intake fraction of a pollutant involves detailed analysis of physical and chemical pathways it may follow to potentially expose a certain population. The overall impact of a source is then the product of its intake fraction and the pollutant mass produced by this source [3]. Subsequently, the exposure impacts for different sources can be calculated and the relative magnitudes of their effects can be compared.

Modeling emission characteristics, meteorology, local conditions, and demographics of the nickel mining, gasoline production, and metal recycling industries in order to compare the human exposure potential of vehicular stack emissions with vehicular tailpipe emissions is beyond the scope of this thesis. However, an order-of-magnitude ranking of different sources is an alternative to compare exposures. Kandlikar and Ramachandran (2000) [3] suggest the use of an appropriate scale to compare intake fraction measures across different contexts. This effectively means that emissions from the tailpipe of a vehicle during its use-phase are associated with a different level of human exposure than pollutants emitted from mining, gasoline production, and metal recycling facility smokestacks. This factor is mainly a function of population density; in North America, urban areas, where vehicles are

driven, are characterized by a high human population density and remote locations, where industry tends to be located, have lower population densities.

## 4.2 THE ENVIRONMENTAL AND HUMAN HEALTH IMPACT OF THE HEV LIFECYCLE VERSUS THE ICEV LIFECYCLE

Due to data constraints, a certain degree of equivalency is required. Consequently, four key assumptions are made:

1) The only additional nickel in an HEV relative to an equivalent ICEV is contained within the NiMH battery and amounts to approximately sixteen kilograms of primary nickel per vehicle.
2) Emissions from the extraction of materials other than nickel for the NiMH battery are equal for HEVs and equivalent ICEVs and small compared to use-phase emissions;
3) Emissions from vehicle manufacturing are equal for HEVs and equivalent ICEVs and small compared to use-phase emissions; and
4) Emissions from the vehicle post-use phase other than NiMH battery recycling are equal for HEVs and equivalent ICEVs and small compared to use-phase emissions.

By evaluating the nickel and associated emissions produced by the material extraction and post-use phases of the NiMH battery in Chapter 2, the excess air pollutant emissions of the HEV lifecycle outside of the use-phase (see assumptions 2, 3, and 4) are effectively established. The use-phase emissions are then derived from Chapter 3. In Table 4.1, an overall lifecycle comparison of HEV and ICEV emissions is calculated using the assumptions listed above and the findings of Chapters 2 and 3. Although excluded from the chapters themselves, for the purpose of conducting a thorough lifecycle assessment, carbon dioxide emissions are included in this final analysis.

Four use-phase scenarios are used to evaluate the role that user behaviour and vehicle usage has on the lifecycle emission savings of HEVs over ICEVs.

- **Scenario 1 (Urban/Low Mileage):** Characterized by predominantly city driving (90% city driving and 10% highway driving), average household lifetime mileage of 145,000 miles over 13 years [4], and four vehicle starts per day with 43% of all vehicle starts being cold. This

scenario is meant to represent the average city dweller that commutes to work, works all day, and commutes home.

- **Scenario 2 (Urban/High Mileage):** Characterized by predominantly city driving (90% city driving and 10% highway driving), with over 200km driven per day (500,000 miles over 10 years), and ten vehicle starts with one start per day being a cold-start. This scenario is meant to represent a taxi driver in a municipal setting.
- **Scenario 3 (Rural/Low Mileage):** Characterized by predominantly highway driving (10% city driving and 90% highway driving), average household lifetime mileage of 145,000 miles, with four daily trips and every start being a cold-start. This scenario is meant to represent a user who lives in a suburban setting with few stop lights and either has a short commute or telecommutes.
- **Scenario 4 (Rural/High Mileage):** Characterized by predominantly highway driving (10% city driving and 90% highway driving), higher mileage (ie. a long commute), and four trips per day with 43% of the vehicle starts being cold. This scenario is meant to represent a user who lives in a suburban setting with few stoplights, has a long commute, and takes few trips outside of his/her daily commute to and from work.

**Table 4.1. Lifecycle Emissions of MY2001 Toyota Prius and MY2001 Toyota Corolla (kg)**

| | | $CO_2$ | Criteria Air Pollutants | | | | | Other Pollutants | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | CO | NOx | HC | SOx | PM | Ni | $NH_3$ | Cu | As | Pb |
| **Material Extraction Phase (Ni)*** | Prius | 234.39 | 0.67 | 0.80 | 0.22 | 19.05 | 0.63 | 0.033 | 0.10 | 0.0084 | 0.0067 | 0.0045 |
| | Corolla | 15.59 | 0.044 | 0.053 | 0.015 | 1.27 | 0.042 | 0.0022 | 0.0065 | 0.00056 | 0.00045 | 0.00030 |
| | Difference | -218.80 | -0.62 | -0.74 | -0.21 | -17.79 | -0.58 | -0.031 | -0.091 | -0.0078 | -0.0063 | -0.0042 |
| | % Difference | -1403.5 | -1403.5 | -1403.5 | -1403.5 | -1403.5 | -1403.5 | -1403.5 | -1403.5 | -1403.5 | -1403.5 | -1403.5 |
| **Post-Use Phase** | Prius | ng/e | ng/e | ng/e | ng/e | ng/e | ng/e | 0.62 | ng/e | ng/e | ng/e | ng/e |
| | Corolla | ng/e | ng/e | ng/e | ng/e | ng/e | ng/e | 0.30 | ng/e | ng/e | ng/e | ng/e |
| | Difference | - | - | - | - | - | - | -0.32 | - | - | - | - |
| | % Difference | - | - | - | - | - | - | -105.3 | - | - | - | - |
| **Use Phase (Scenario 1)** | Prius | 29838.36 | 40.28 | 7.09 | 5.67 | 0.14 | 0.05 | | | | | |
| | Corolla | 45233.38 | 89.58 | 8.23 | 7.77 | 0.21 | 0.07 | | | | | |
| | Difference | 15395.03 | 49.30 | 1.14 | 2.10 | 0.07 | 0.02 | | | | | |
| | % Difference | 34.0 | 55.0 | 13.9 | 27.0 | 34.0 | 34.0 | | | | | |
| **Use Phase (Scenario 2)** | Prius | 102678.45 | 122.01 | 22.33 | 15.92 | 0.47 | 0.16 | | | | | |
| | Corolla | 155655.14 | 222.71 | 24.44 | 21.43 | 0.72 | 0.24 | | | | | |
| | Difference | 52976.69 | 100.70 | 2.11 | 5.51 | 0.24 | 0.08 | | | | | |
| | % Difference | 34.0 | 45.2 | 8.6 | 25.7 | 34.0 | 34.0 | | | | | |
| **Use Phase (Scenario 3)** | Prius | 26703.37 | 39.80 | 6.64 | 4.96 | 0.12 | 0.04 | | | | | |
| | Corolla | 39859.12 | 77.45 | 8.01 | 6.65 | 0.18 | 0.06 | | | | | |
| | Difference | 13155.75 | 37.66 | 1.36 | 1.68 | 0.06 | 0.02 | | | | | |
| | % Difference | 33.0 | 48.6 | 17.0 | 25.4 | 33.0 | 33.0 | | | | | |
| **Use Phase (Scenario 4)** | Prius | 91890.47 | 103.10 | 22.79 | 14.64 | 0.42 | 0.14 | | | | | |
| | Corolla | 137161.46 | 219.25 | 20.82 | 19.35 | 0.63 | 0.21 | | | | | |
| | Difference | 45270.99 | 116.14 | -1.96 | 4.71 | 0.21 | 0.07 | | | | | |
| | % Difference | 33.0 | 53.0 | -9.4 | 24.3 | 33.0 | 33.0 | | | | | |

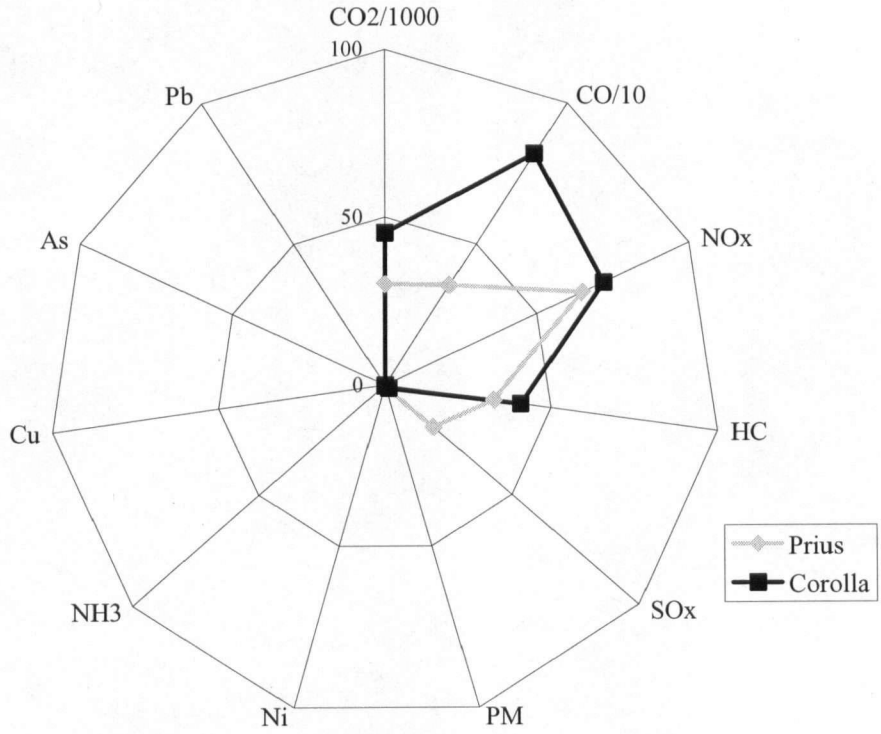
Notes:
"ng/e" – value for ICEV and HEV are equivalent and negligible.
Use-phase emissions are an aggregation of tailpipe and fuel cycle emissions over the lifecycle of the vehicle.
% difference denotes difference in emissions of Prius and Corolla as a fraction of emissions from the Corolla.
Negative difference denotes total for Prius higher than Corolla.
See above for a description of use-phase scenarios.
Manufacturing phase is omitted under the assumption that emissions are negligible and equal for HEV and equivalent ICEV.
* Emissions are for the extraction of primary nickel only. For the Prius this amounts to 16kg for the NIMH battery and 1.14kg for other primary nickel applications; for the Corolla, this amounts to 1.14kg.

Table 4.1 demonstrates that the NiMH battery lifecycle releases pollutants outside of the boundary of the local emissions reductions achieved by the HEV use-phase. Using the concept of the intake fraction of stack versus vehicular tailpipe emissions, the overall effect of this imbalance can be evaluated.

### *4.2.1 Human Health Impact of the HEV versus ICEV Lifecycle*

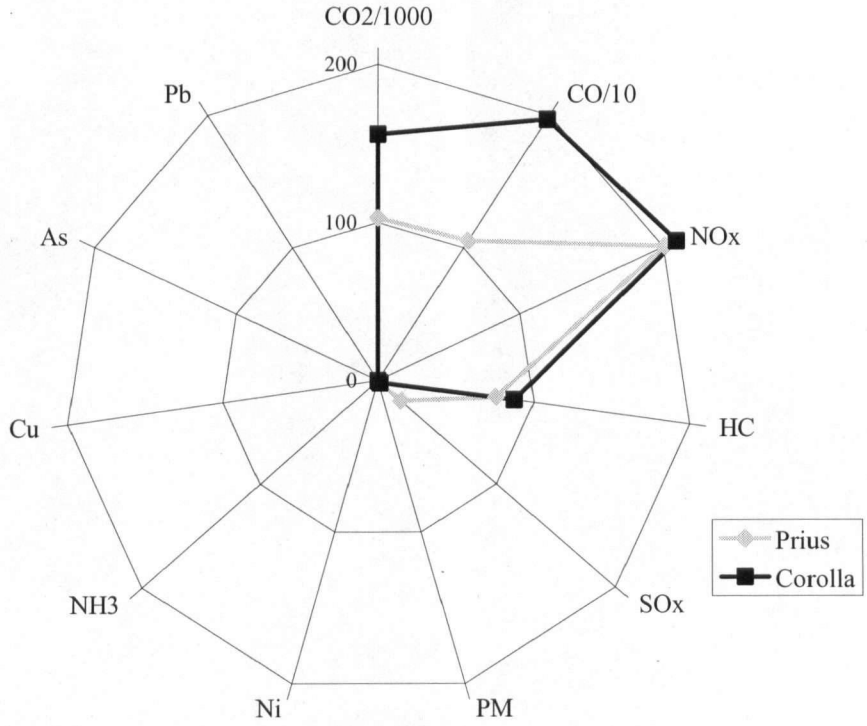
According to [3] and [5], the intake fraction of vehicular tailpipe emissions is an order of magnitude greater than industrial stack emissions. Thus, for the figures below, tailpipe emissions produced in the use-phase are multiplied by a factor of ten (with the exception of $CO_2$) and fuel cycle, material extraction, and post-use phase emissions are multiplied by a factor of one. Figure 4.1 illustrates the contrast between the MY2001 Toyota Prius and Corolla emissions impact upon human health over their respective lifecycles for Scenario 1 and Figure 4.2 does the same for Scenario 2.

**Figure 4.1 Lifecycle Scenario 1 Emissions Impact of MY2001 Toyota Prius Versus Toyota Corolla (kg)**




Notes:
Scenario 1 is characterized by 90% city driving and 10% highway driving, 145,300 lifetime miles, and 4.4% of VMT in cold operation.

**Figure 4.2 Lifecycle Scenario 2 Emissions Impact of MY2001 Toyota Prius Versus Toyota Corolla (kg)**




Notes:
Scenario 2 is characterized by 90% city driving and 10% highway driving, 500,000 lifetime miles, and 0.64% of VMT in cold operation.

Given the difference in scale between Figures 4.1 and 4.2, it is apparent that the strict magnitude of the miles traveled has a large effect on the lifetime emissions produced from the vehicle tailpipe in its use-phase. In either case however, it can be concluded that the higher emissions associated with the Prius material extraction and post-use phases relative to the Corolla are outweighed by the substantial emissions improvements incurred in the use-phase due to the tonnage of pollutant reductions and the levels of human exposure with which it is associated. Proportionally, there is a slight decrease in lifecycle emissions benefit from Scenario 1 to Scenario 2 (average mileage to higher mileage with fewer cold-starts). From a 'mass of pollutants reduced' perspective however, a larger quantity of emissions are reduced through more driving of the HEV.

### *4.2.2 Environmental Impact of HEV versus ICEV Lifecycle*

Generally speaking, in areas where there is potential for elevated human exposure there is less opportunity for environmental damage given the prevalence of concrete and asphalt surfaces over

vegetative cover. It could then be argued that the human health intake fraction of emissions from vehicular tailpipes and industry smokestacks could be reversed for environmental damages. In other words, industrial emissions have an environmental intake fraction an order of magnitude greater than vehicular tailpipe emissions. When this calculation is performed, the HEV use-phase improvements still outweigh the stack impacts; however environmental impacts of fuel cycle emissions of $SO_x$ and PM, which are not made up for at the tailpipe, are slightly higher. This impact is discussed in the following section.

### *4.2.3 Conclusions about the HEV Lifecycle*

From an inventory perspective, this research has quantitatively verified tailpipe pollutant emissions benefits of HEVs over ICEVs and has concluded that additional upstream emissions associated with the lifecycle of the NiMH battery add to the emissions footprint of the HEV. However, as stated in Section 1.8, the research objective of this thesis is to examine whether the *impact* of the additional nickel and associated releases emitted to the environment from the HEV lifecycle are outweighed by the *impact* of emission reductions in the use phase relative to an equivalent conventional ICEV. Simply put, Figures 4.1 and 4.2 illustrate that the Prius lifecycle impact is smaller than that of the Corolla when emissions of all air pollutants examined in this study are put together in using an intake fraction calculation.

From the four scenarios, five main conclusions can be drawn about HEV emissions as compared to an equivalent ICEV:

- With more vehicle miles traveled, reductions in $CO_2$ and CO increase proportionally;
- CO and $NO_x$ emissions are preferentially reduced when the HEV is operating under cold-start conditions;
- HC emissions are only modestly reduced over all phases of vehicle operation;
- With more vehicle miles traveled, HEV reductions of NOx emissions are smaller over the vehicle's lifecycle due to higher emissions in the stabilized phase; and
- HEV benefits are maximized in an urban setting where more vehicle starts generally occur in daily use and the vehicle drives further in cold- and hot-start rather than stabilized operation.

As demonstrated, the HEV is not exempt from gaining local environmental benefit at the cost of transferring discharges elsewhere. The most important difference between the stack emissions of the Prius and Corolla is $SO_x$. $SO_x$ is a criteria pollutant with respiratory impacts upon human health and

acidification effects upon ecosystems. It is produced during the nickel extraction and fuel cycle stages of the HEV and ICEV lifecycle therefore it is not emitted at the local level. It is slightly reduced in the fuel cycle phase, given the higher HEV fuel economy, however a surplus of $SO_x$ remains over the lifecycle of an HEV as compared to an equivalent ICEV. $SO_x$, is highly controlled and regulated due to its potential for and history of environmental degradation. Subsequently, emissions from smelters have been reduced by more than 90% since 1980 through better emissions control [6] and a slow ecosystem recovery is on its way [7]. Similarly, emissions of Ni, Pb, As, Cu, PM and $NH_3$ are an order of magnitude larger over the lifecycle of an HEV than an ICEV, however the tonnages of these pollutants are low relative to the tailpipe emissions. Like $SO_x$, these pollutants represent only 1% of the releases associated with the existing nickel mining industry and their impact on human health is reduced due to the remote location and therefore low population density of the nickel mining and refining activities.

## 4.3 STRENGTHS AND WEAKNESSES OF THE THESIS RESEARCH

A strength of this research is its relevancy to ongoing debates in the public and academic forums and the ability of this work to inform a number of groups, hopefully through the publication of Manuscript 1 and/or 2. Past LCAs of HEVs have concentrated on fuel use, economics, and GHG emissions. This work contributes to the existing research because it adds criteria pollutant and NiMH lifecycle emissions to HEV LCA knowledge. Future research surrounding the economic-ecological evaluation of HEV technology could use the findings of this thesis to put a dollar value upon nickel and associated emissions, use-phase criteria pollutant savings, and cold-start emissions improvements.

There are no economic conclusions in the analysis. This is a weakness from the perspective of being able to use this analysis for policy or consumer interest purposes. However, applying damage values or some other monetary metric to the pollutant reductions could resolve this limitation.

Data acquisition and availability was a challenge in this work, often causing assumptions to be made in place of using actual facts. Information about vehicle material composition is often proprietary therefore industry consumption statistics were used in place of actual manufacturer specifications. Presently, nickel battery recycling, specifically for HEV applications, is an area with few publications and little manufacturer-provided information which made accessing data regarding emissions difficult. This lead to assumptions of little environmental impact and emission, when this process in the HEV lifecycle could potentially contribute significantly to the magnitude of transferred pollutants.

All information was acquired from outside sources - no first hand data accumulation was performed making external validation of the data difficult. Industry statistics published by organizations such as NRCan and the USGS are generally deemed reliable, however emissions information either provided by industry or independent organizations involves data accumulation and analysis methodologies that could not be confirmed by the researcher.

## 4.4 FURTHER RESEARCH OF VALUE

The accurate measurement of HEV use-phase emissions is essential to gaining a complete picture of their performance with respect to equivalent ICEVs. Research upon emissions testing procedures that accurately depict HEV emissions over a complete driving cycle and a more complete understanding of the emissions implications of the number of engine start/stops HEVs undergo in an average drive cycle would be valuable contributions to the field of HEV emissions characterization. Also, emissions testing of HEVs in the stabilized phase would be a valuable addition to this work in order to verify that $NO_x$ emissions in this phase are indeed higher than an equivalent ICEV.

Little information was available on the topics of NiMH battery manufacturing and recycling processes and associated emissions. With the acquisition of such information, a more informed nickel material flow could be performed. More importantly, as HEVs currently on the road approach the end of their useful lives, processes for recycling, although most likely already existing, will need to be maximized for efficiency and profit, thus research on this topic will become more and more timely.

As with any technology, HEVs are constantly evolving and improving in terms of vehicle and environmental performance. In the near future, it is proposed that NiMH batteries will be replaced with lithium-ion (Li-ion) batteries. A valuable topic of research would be a material flow analysis of the Li-ion battery technology, with the goal of determining its environmental and human health impact compared to the NiMH battery technology. Similarly, economics often drive the choice of technology in industry, therefore a lifecycle cost analysis of Li-ion versus NiMH batteries would be useful to manufacturers.

The analysis conducted in both manuscripts could be expanded in a few different ways, two of which are listed here. Firstly, HEVs, nor nickel, are confined to North America therefore a broader boundary

around the NiMH analysis – perhaps one of global proportions would be a valuable analysis. Secondly, supplementing the human health and environmental impact findings of this analysis with a monetary metric would round out the analysis into an economic-environmental analysis similar to those of Lave & Maclean [8,9].

## 4.5 POTENTIAL APPLICATIONS OF RESEARCH FINDINGS

The need for accurate representation of HEVs in emission testing is highlighted in order to properly understand and quantify the improvements HEVs actually offer in real world driving conditions. Reliable testing procedures that yield representative results, can inform policymakers and vehicle manufacturers about the degree of HEV endorsement they should participate in.

The findings of this research could be used in emissions inventory or modeling applications of lifecycle emissions of HEVs. Such analyses might be conducted by individual vehicle owners, fleet operators, manufacturers, or any operator whose emissions are regulated. Individually, manuscript 1 provides a useful framework for the Li-ion material flow analysis suggested in section 4.3. Manuscript 2 highlighted the need to specially consider cold-start emissions savings during HEV emissions testing in order to get representative drive cycle characterization. This is valuable information to regulatory and in-use emission testing facilities looking to adapt present vehicle testing procedures to HEV drivetrains.

New technologies are contentious for many reasons, and HEVs are no exception. They are more expensive than conventional vehicles, they have a certain environmental/status stigma attached to them, and they are claimed to achieve local air pollution and fuel consumption improvements. For all of these reasons and more, there are many supporters of this technology and many detractors. Both groups have strict opinions regarding the environmental benefits and/or detriments HEVs impart over their lifecycle. This analysis allows informed conclusions to be drawn regarding air emissions specifically, including those resulting from the NiMH battery lifecycle which up until now had not yet been done. Presenting the conclusions and findings of this thesis in a public forum could act to inform policy and consumers about the technology.

## 4.6 REFERENCES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# APPENDIX A

**Table A1. Regulatory and In-Use Fuel Economy Estimates for MY2001 Vehicles (L/100km)**

| | EPA Revised Fuel Economy Estimate | EPA "Your MPG" Fuel Economy Estimate |
|---|---|---|
| Toyota Prius | 5.77 | 5.10 |
| Toyota Corolla | 7.89 | 7.66 |
| Toyota Echo | 7.89 | 6.68 |
| Honda Civic | 8.16 | 6.90 |

**Figure A1. 2001 Toyota Prius Government Fleet In-Use Fuel Economy**

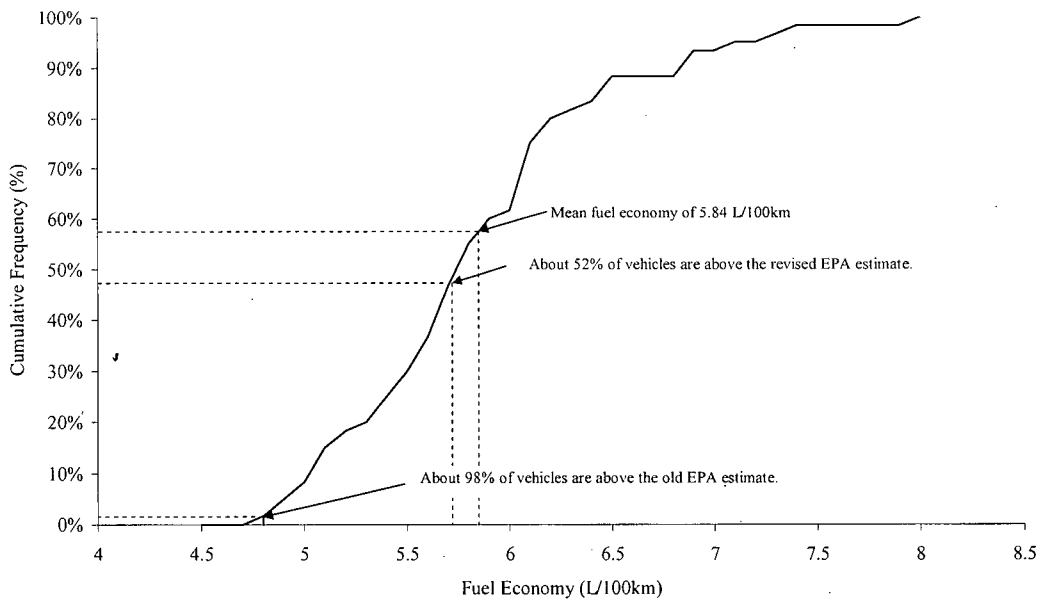

**Figure A2a. 2001 Toyota Prius AirCare CO Emission Factors**

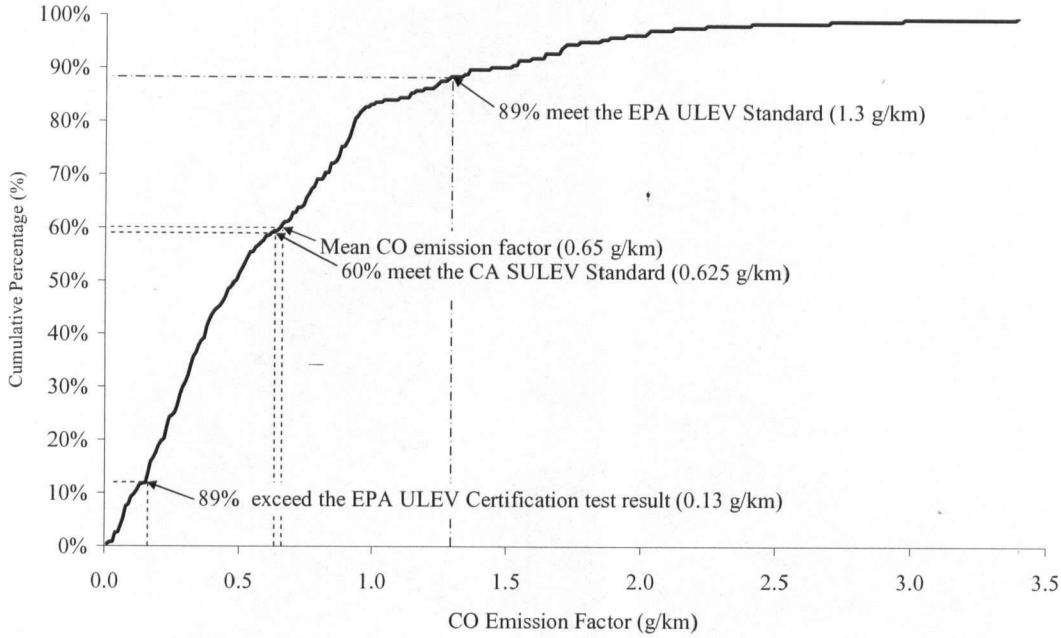


**Figure A2b. 2001 ICEV AirCare CO Emission Factors**

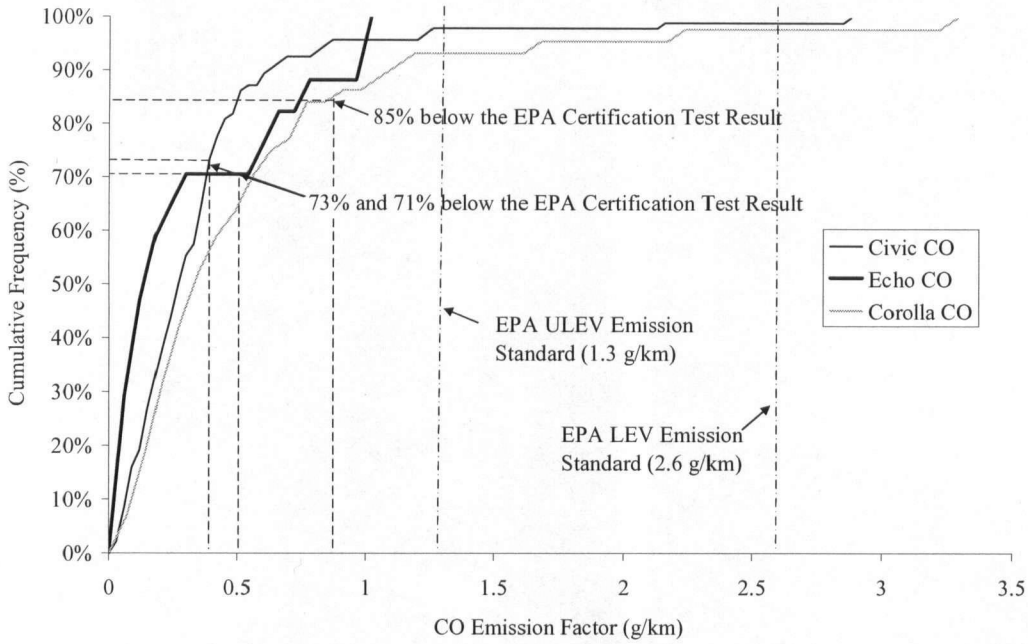

**Figure A3a. 2001 Toyota Prius AirCare HC Emission Factors**

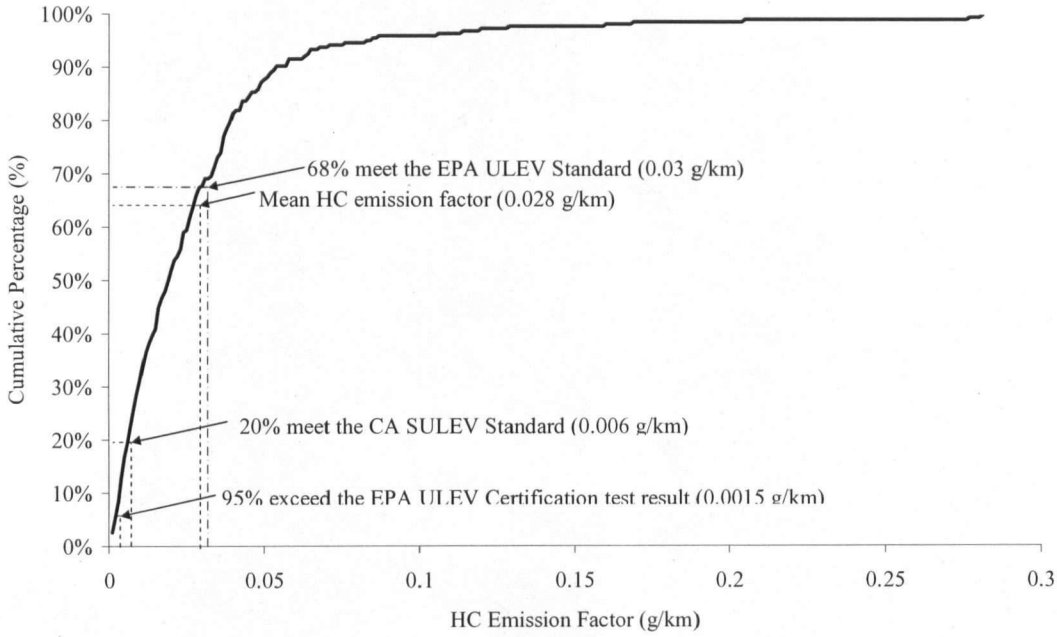


**Figure A3b. 2001 ICEV AirCare HC Emission Factors**

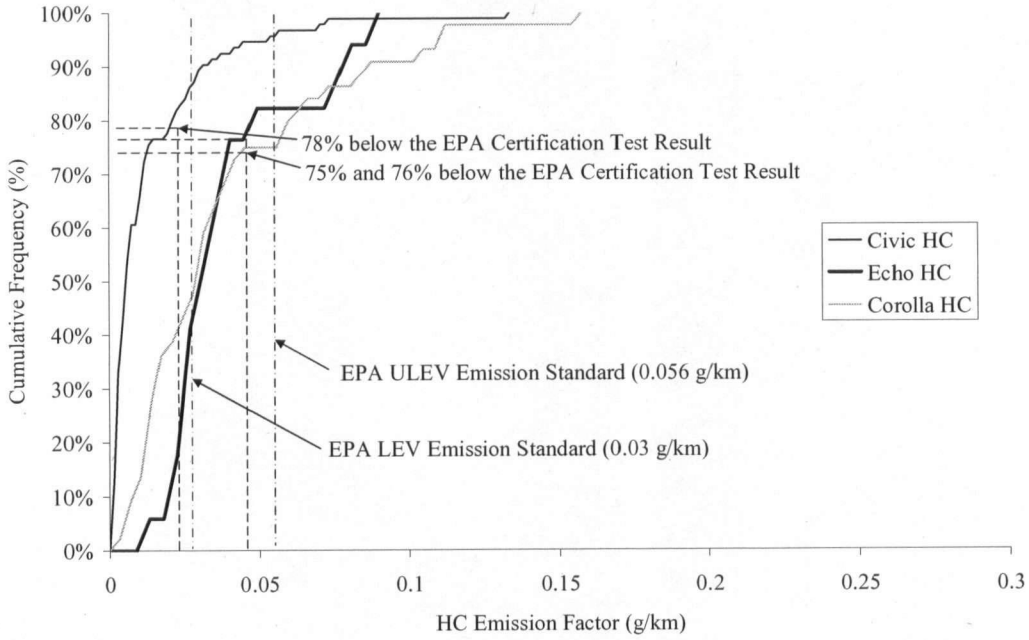

**Figure A4a. 2001 Toyota Prius AirCare NOx Emission Factors**

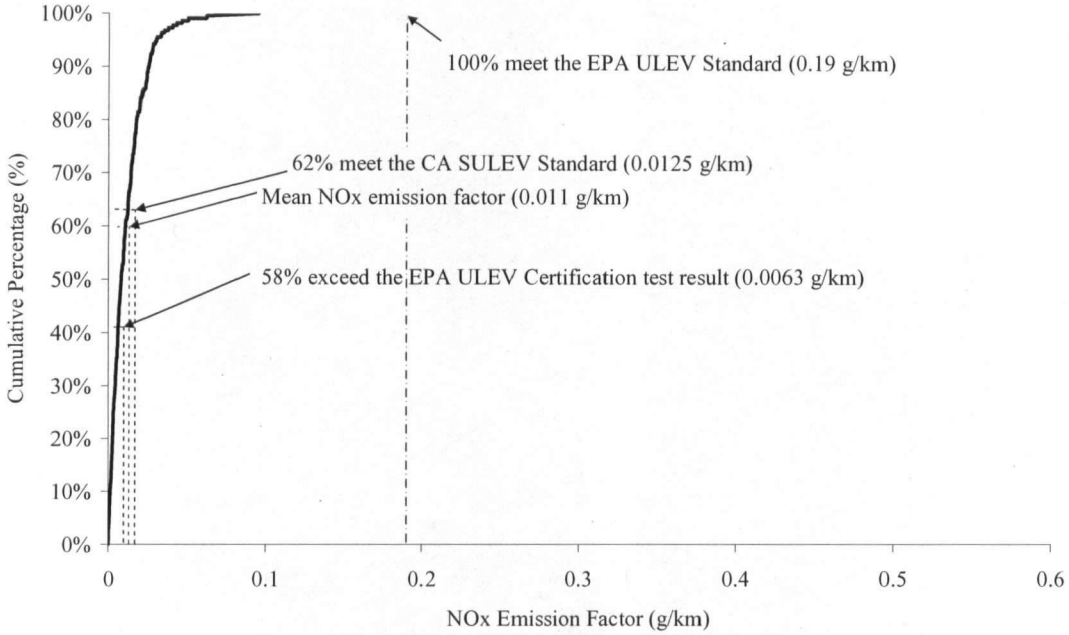


**Figure A4b. 2001 ICEV AirCare NOx Emission Factors**