From Smoke to Mirrors

How New Zealand can replace fossil liquid fuels with locally-made renewable energy by 2040

Kevin Cudby

Hydraulic Press Limited

* * * *

First published in 2010 by
Hydraulic Press Limited
PO Box 38 209
Wellington 5045
New Zealand
http://fromsmoketomirrors.com

Smashwords Edition published 2012

Cover

The cover represents concepts relevant to liquid fuels and climate change: oil refining, thermochemical fuel production, forests, rural road transport, the sea, and storms. Above all, is the hope for a peaceful global transition from fossil fuels to renewable energy. (Images: Light and clouds Copyright Milije54, Dreamstime.com; Refinery Copyright Benkrut, Dreamstime.com; Solar power tower Copyright Quintanilla, Dreamstime.com; Mainfreight truck Copyright Mainfreight Limited.)

Design and typesetting by Mills Design: www.millsdesign.co.nz

* * * *

For Emily and Ryan

* * * *

Contents

Acknowledgements
Introduction
Chapter 1: Fossil Fuels Must Be Eliminated
Chapter 2: How New Zealand Uses Liquid Fuel
Chapter 3: Internal Combustion Engines
Chapter 4: Battery Vehicles
Chapter 5: Battery Vehicles–Generating the Power
Chapter 6: Battery Vehicles–Distributing the Power
Chapter 7: Battery Vehicles–Prospects
Chapter 8: Hybrid Vehicles
Chapter 9: Hydrogen Fuel Cell Vehicles
Chapter 10: Hydrogen Fuel Cell Vehicles–Infrastructure
Chapter 11: Hydrogen Fuel Cell Vehicles–Prospects
Chapter 12: Synthetic Fuels–Fischer-Tropsch
Chapter 13: Energy Forests
Chapter 14: Synthetic Fuels–Hydrothermal Liquefaction
Chapter 15: Biofuel from Aquatic Algae
Chapter 16: Alternative Biofuels–Biodiesel
Chapter 17: Alternative Biofuels–Ethanol
Chapter 18: Assessing the Options
Chapter 19: How to Carbon-Neutralise New Zealand’s Fuel Supply
Chapter 20: The Carbon-Neutral Fuel Market
Chapter 21: A Strategy for Action
Chapter 22: The Global Context
Afterword: Population
Notes
About the Author

* * * *

Acknowledgements

I doubt I could have finished this book without the unstinting support of my wife Diana. Her proof-reading, critique and suggestions have been invaluable. Thanks, also, to my good friend Tatjana Shäfer, for her gentle but firm critique.

I owe my parents an unfathomable debt of gratitude for their tolerance and support; and my father for his vast knowledge of automotive technology: from gas producers to compressed natural gas and diesel.

I also want to thank Chris Else for believing in this project, and Ross Mills for patiently coping with chaos as he converted the manuscript into a book.

The list of people I have interviewed, and the reports I have read, could easily fill a book. I sincerely thank all the people I have interviewed, and all the writers whose work I have studied.

I have collected and sifted an enormous amount of information. I must stress that any errors or omissions are my own, and no-one else's.

Finally, I must recognise the work of Eliyahu Goldratt. His book *The Goal* and his *Theory of Constraints* inspired the foundation on which this book was built.

* * Table of Contents * *

Introduction

This book evolved from a simple idea: That civilisation depends on an integrated system of production and distribution. Key parts of this system are powered by liquid fuels, most especially diesel. Humanity can improve its long-term viability by reducing the impact of production and distribution on the global climate. To do so, every present-day application of liquid fossil fuels must be replaced with a practical carbon-neutral or carbon-free alternative that is at least as effective as today's technology.

Transport is central to our production and distribution system. Land transport, and especially road transport, embodies humanity's most fundamental inventions: Fire and the wheel. Perhaps that is why the car inspires such strong emotions. Its engine depends on fire: Its mobility depends on the wheel. Beyond its practical application, the car is a metaphor for human inventiveness. But this book's underlying mission is not to reinvent the car, but to learn how humanity might reinvent all the activities that depend on liquid fossil fuels. When we load groceries into the back of a car, it becomes the final link in our food distribution system. That system depends on many other types of machines, most of which run on diesel. We don't often think about how food gets from paddock to pantry, as long as we can keep the pantry stocked.

To understand how various possibilities might eliminate liquid fossil fuels from New Zealand's economy, I focussed on constraints. Having enough food in the pantry is a constraint. Land is a constraint. The planet is not getting bigger, and from the practical perspective, neither are New Zealand's shaky islands.

We are interested in tonne-kilometres of freight; in passenger-kilometres; in hectares of land. Biofuel production requires land. So does solar power: It takes a certain area of solar panels to make enough electricity to shift a certain amount of freight. The amount of power is not, in itself, a constraint.

Focussing on real constraints often yields solutions to problems that confound and bewilder theoreticians. That is as it should be. Good theory evolves from practical experience: If a theory does not agree with reality, it's useless.

Our search for climate-friendly alternatives to liquid fossil fuels does not begin with a blank slate. The most promising technologies were identified during the 1970s. Many researchers and engineers have continued to develop them, and several excellent technologies are now approaching commercial reality.

Laboratory scientists occasionally announce discoveries that might, one day, contribute to the world's transport systems. But it takes decades for new energy technologies to evolve from laboratory experiments to practical reality, so it is tempting to ignore these fresh proposals. This is not necessary or desirable. We can design the transition to renewable energy so that new technologies drop into place when they are ready.

I was astounded by some of the conclusions that flowed naturally from the research behind this book. But I was also delighted to learn that planning the transition from liquid fossil fuels to renewable energy is far less complex than I could have imagined at the beginning of this project. It will be challenging and difficult, but I am convinced we know what to do.

Join me on a technological tour of the future. I will show you the technologies that will work in New Zealand, but I will not ignore technologies that will be vital overseas. Researching this book has taught me that New Zealand can eliminate liquid fossil fuels from every corner of its economy by 2040. I will describe what New Zealand must do, and what the world can learn from New Zealand's success.

* * Table of Contents * *

Chapter 1: Fossil Fuels Must Be Eliminated

It's not often European motor racing makes the six o'clock news in New Zealand, but Audi's victory in the 2006 Le Mans was different. Not only had they built a sportscar that ran on tractor fuel, Audi's diesel-burning R10 had won the world's premier sportscar race.

Petrolheads cried foul. Diesels use less fuel than petrol engines, so the Audis made fewer pitstops, spending more time racing and less refuelling. A rule-change for 2007 reduced the fuel capacity of diesel-powered Le Mans cars, but it wasn't enough. Audi won, and a diesel-burning Peugeot came second. It was looking very much as though French motor racing authorities were purposely stacking the odds in favour of diesels.

France is one of twenty-seven countries that, as members of the European Union, are committed to drastically reducing greenhouse gas emissions. If France is to pull its weight, shouldn't its motorsport officials encourage technologies that reduce carbon dioxide emissions? Carbon dioxide is by far the dominant greenhouse gas emitted by motor vehicles: The only way to stop an internal combustion engine producing carbon dioxide is to switch it off. Litre for litre, diesel has more carbon than petrol, so burning a litre of diesel produces more carbon dioxide. So what's going on? Why are the rules for Le Mans racing cars biased in favour of diesels? Shouldn't they encourage fuels that contain less carbon? Such as ethanol, which is only fifty-five percent carbon? Or hydrogen, which has none?

Liquid Fuels and Climate Change

World-wide, fossil fuel consumption is the largest source of anthropogenic, or human-made, greenhouse gas emissions, the underlying cause of human-made climate change. Most fossil fuels are used for energy production, which accounts for more than sixty percent of anthropogenic greenhouse emissions. Most energy-related emissions come from electricity, heat, transport, and non-transport liquid fuel, all of which are dominated by fossil fuels. Most of the world's electricity comes from coal-fired power stations, and oil, coal, and natural gas, are the world's main sources of heat. Road, air, and sea transport runs almost exclusively on liquid fossil fuels: petrol, kerosene (jet fuel), diesel, and fuel oil. Most electrified railways get their juice from gas and coal-burning power stations. Almost all non-electrified railways run on diesel. It is true that some industrial processes, such as cement and steel manufacturing, also consume a great deal of coal and pump out shiploads of carbon dioxide. But the big emitters are electricity, heat, transport, and non-transport liquid fuel.

Scientists have known for more than fifty years that fossil fuel consumption can affect the global climate. In the 1950s, US scientists Roger Revelle and Hans Suess wondered if we might learn something about climate and the weather by studying what happens to anthropogenic greenhouse gases after they pour out of our tailpipes:

> *... human beings are carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years. This experiment, if adequately documented, may yield a far-reaching insight into the processes determining weather and climate. It therefore becomes of prime importance to attempt to determine the way in which carbon dioxide is partitioned between the atmosphere, the oceans, the biosphere and the lithosphere.*[1]

By the 1970s a basic understanding of long-term climate variation was beginning to emerge. John and Katherine Imbrie described, in their 1979 book about the ice ages, how scientific research over many decades had identified the most important factors. Variations in the earth's movement through space over timescales of tens of thousands of years affect the distribution of solar energy across the earth's surface. A blanket of greenhouse gases, mainly water vapour and carbon dioxide, trap solar energy in the atmosphere and oceans. Together, these concepts are the main foundation of what the Imbries called the *Astronomical Theory of the Ice Ages*. For the past million years or so, the earth has experienced a repetitive pattern of ice ages lasting tens of thousands of years, punctuated by warm periods, or inter-glacials. The current warm period began about 11,000 years ago, and is expected to last another ten to twenty thousand years. If it weren't for human activities, said the Imbries: *23,000 years from now, the earth would once more find itself in the depths of a new ice age*[2].

Human civilisation will never face the challenge of adapting to another ice age. Engineers can easily compensate for global cooling by intentionally pumping greenhouse gases into the atmosphere.

It is far more difficult to stop the present trend toward a warmer climate.

Climate change is not inherently bad, but many people worry about its effect on the world's human population and the economy that supports it. The most immediate problem is sea level rise. As ocean temperatures gradually increase, the water expands, pushing up the surface of the oceans. Global warming is also melting glaciers and ice caps, increasing the amount of water in the oceans. Rising sea levels threaten coastal communities in countries as diverse as Holland, the USA, Australia, and Bangladesh. Island countries such as Tuvalu, Kiribati, and the Marshall Islands are expected to become uninhabitable by the late twenty-first century.

If, tomorrow, the world could stop using fossil fuels, the carbon dioxide already in the atmosphere would continue to influence the global climate for many decades into the future, because carbon dioxide stays in the atmosphere for centuries. The sooner fossil fuel consumption stops, the sooner global temperatures will stabilise. And, the sooner global temperatures stop rising, the sooner sea levels will stabilise.

That's why experienced climate scientists are calling for a rapid move away from fossil fuels. Back in the 1950s, some scientists knew fossil fuel consumption would affect the climate, but most did not think this was potentially dangerous. By the 1970s, it was becoming clear that human-made climate change would overwhelm the natural pattern of climate variation, beginning in the late twentieth century. By the 1990s, many scientists were confident human consumption of fossil fuels would cause serious problems. Now they are certain, and they are worried.

Reducing Emissions is Not Enough

A car buyer can reduce their greenhouse emissions by choosing a diesel car because a diesel engine gets more work from a litre of fuel than a petrol engine. That's why the Audi R10s made fewer pit-stops than their petrol-burning rivals. Racing around a racetrack is a job of work. The diesel car can do more laps on a single tank of fuel.

Diesel cars make less carbon dioxide than petrol cars. Their superior fuel economy outweighs the slightly greater carbon content of diesel fuel, compared with petrol. This partly explains why French motor racing officials can get away with rules that are heavily biased toward diesel: European policy-makers want people to buy diesel cars, not petrol ones.

Switching from petrol to diesel cannot eliminate greenhouse emissions. Merely reducing consumption might slow climate change, but until the world totally eliminates fossil carbon dioxide emissions the seas will keep rising. Unchecked, sea level rise could seriously damage the world's food supply. For example, at current rates of fossil fuel consumption, it is very likely that sea levels in the twenty-second century could disrupt global shipping. Seaports cannot function properly if their wharves are underwater.

Non-Road Liquid Fuels are Critical

No-one, anywhere in the world, has come up with a realistic plan for eliminating fossil liquid fuels. Car and truck manufacturers are developing road vehicles powered by energy sources such as batteries and hydrogen. But fixing road transport cannot eliminate liquid fossil fuels from the global economy.

Almost half of New Zealand's fossil liquid fuels are burned in non-road applications such as agriculture and construction. Liquid fuels are crucial to shipping and aviation, and because New Zealand is so far from its trading partners, air and sea transport are fundamental to its economic well-being. This may explain why non-road liquid fuels represent such a high proportion of New Zealand's total consumption. I estimate non-road liquid fuels account for thirty percent of global oil consumption[3], whereas forty percent of liquid fuels in New Zealand are sold to non-road users.

Diesel is by far the most important non-road liquid fuel. Modern food production systems depend critically on diesel fuel and diesel engines. Tractors, harvesters, and other agricultural machinery are usually powered by diesel. Most fishing boats run on diesel. Food-producing industries also depend on diesel trucks to transport produce from the farm, vineyard, or market garden. This is true of all modern food production systems in all parts of the world. Organic farmers rely on diesel just as much as industrial farmers. Giant diesel tractors are equally at home in the Russian Far East, the Midwestern US, or in the Manawatu or Canterbury.

To fully grasp the importance of non-road liquid fuels, consider what would happen if, tomorrow, the world ran out of crude oil. Imagine road transport switched to climate-friendly renewable energy. And suppose the world's entire supply of non-road liquid fuels was changed, overnight, to fuel made from high-grade coal using well-proven *Coal-to-Liquid* processes.

Global greenhouse emissions would not change.

Why?

Because the total carbon dioxide emissions from coal-to-liquid fuels will be more than three times greater than total emissions from conventional fuels. High-grade coal is mostly carbon, with very little hydrogen. So, the coal-to-liquid process makes some hydrocarbon fuels, and lots of carbon dioxide. Almost one third of the world's supply of liquid fuels goes to non-road users. Coal-to-liquid fuel would more than treble their greenhouse emissions. That's enough to cancel out the benefit of carbon-neutralising cars, trucks, and buses.

The world will not run out of oil tomorrow, but there's no doubt oil is a finite resource. Eventually, non-road liquid fuel consumers will need an alternative. But the world has plenty of fossil-based options. A recent IEA projection suggests humanity might eventually produce more than seven trillion barrels[4] of liquid fuels, over and above the trillion or so barrels that have already been used. Engineers know how to make liquid fuels from all the fossil resources: conventional and heavy oil, natural gas, tar sand, oil shale, and coal. If it weren't for climate change, alternative fossil fuels such as coal would be fine[5].

So, although some countries are working very hard to reduce greenhouse emissions from road transport, this is not enough. Unless non-road liquid fuel users change to carbon-neutral technology, it is very likely greenhouse emissions will continue to increase, even after the world eliminates fossil fuels from road transport.

The Opportunity for New Zealand

This situation creates an enormous opportunity for New Zealand, an opportunity that could put us at the forefront of efforts to combat one of the largest problems facing the international community. We can become the first country in the world to carbon-neutralise our transport system, which is one of the main components of our energy system. We can also replace all non-transport liquid fuel with carbon-neutral energy.

The necessary technologies have been known for decades, and they are now very close to commercial reality. This book will survey these technologies and look at how New Zealand can use the combination of new energy technologies and indigenous energy resources to eliminate fossil liquid fuels from its economy by 2040.

If we choose to do this, New Zealand would have the world's first fully carbon-neutral energy supply. It is comparatively easy to eliminate fossil fuels from the other major part of our energy system, electricity production.

But why fix electricity, transport, and non-transport liquid fuel? Why not fix agriculture? which is our largest source of human-made greenhouse gases.

The most important reason for attacking liquid fuels is that we can show the rest of the world how to solve a critical part of the problem. If, tomorrow, New Zealand's greenhouse gas emissions magically stopped, that would not make a scrap of difference to human-made global warming. Our contribution to climate change is negligible.

But, if we can show the rest of the world how to solve a difficult part of the world-wide problem, they won't be able to ignore us. In fact, they'll be tripping over each other racing down to New Zealand to find out how we did it and how they might copy our success.

How to Replace Fossil Liquid Fuels

New Zealand will import much of the necessary technology, but we will have to come up with a unique way of putting it into practice. Foreign efforts to deal with climate change are aimed at reducing, but not eliminating, greenhouse emissions. We will be aiming at a different target, so we will probably take a different route toward that goal.

We could deploy a technology that does not emit carbon dioxide, or any other greenhouse gas. This would involve vehicles and non-road machinery powered by rechargeable batteries or hydrogen. It would work only if the electricity or hydrogen comes from sources that do NOT emit greenhouse gases. Electricity and hydrogen are not natural resources. We have to make them.

The other approach is to neutralise the effect of greenhouse emissions, for example, by replacing fossil fuels with biofuels. Biofuels can reduce or eliminate net greenhouse emissions because their consumption does not increase the total amount of carbon circulating in the biosphere. Most fuels, fossil and bio, are made from biological material, which is made from carbon dioxide captured from the atmosphere by photosynthesis. When they are burned, their carbon returns to the atmosphere as carbon dioxide. The trouble with fossil fuels is that their carbon has been out of circulation for many millions of years. Fossil fuel consumption adds carbon to the biosphere (the atmosphere, land surface, and oceans) faster than it is being removed, for example, when dead marine animals become buried in the muddy bottom of the deep ocean. Biofuel consumption, on the other hand, maintains a short-term balance between the carbon dioxide absorbed by growing plants and the carbon dioxide from engines using fuel made from those plants. That's the theory, but very few biofuels achieve this in practice. Some advanced biofuels work, but many of the so-called first generation biofuels do not.

We won't be interested in partial solutions. A biofuel might be the world's cheapest liquid fuel, and it may totally eliminate greenhouse emissions, but unless New Zealand can make enough of it to satisfy a significant fraction of total demand, it's a distraction. This also goes for hydrogen and electricity. If a hydrogen manufacturing technology requires the entire land area of several planets to make enough hydrogen for New Zealand's transport system, it's pointless.

A single solution may not fix everything: for example, battery lawnmowers might prove better than petrol ones, whereas battery-powered aircraft may not compete with jet airliners powered by gas-turbine engines burning kerosene.

In 2008, New Zealand spent more than eight billion dollars on imported oil. Replacing fossil liquid fuels with indigenous energy would largely eliminate this expense. Provided export earnings are not seriously reduced, switching to carbon-neutral energy may improve the financial well-being of all New Zealanders.

If We Build It They Will Come

Long before 2040 the world will want to know how New Zealand is carbon-neutralising its entire energy supply. They might have some ideas about carbon-neutralising their road transport systems, but as we'll see in later chapters, it is far more difficult to deal with non-road liquid fuel. We can show the world how to harness renewable energy in a form that fully satisfies all non-road applications. We can do this by applying skills unique to New Zealanders.

So, although New Zealand's greenhouse emissions are miniscule compared with those of major greenhouse gas emitters, we can make a unique, and vital, contribution to solving this critical problem. To do this, we must look at all the options, and figure out which ones best meet our needs.

* * Table of Contents * *

Chapter 2: How New Zealand Uses Liquid Fuel

Effective transportation requires a fully integrated system, involving all forms of land, sea, and air transport.

This book will focus on road transport, with special emphasis on freight. It will also look at air and sea transport, and non-road machinery such as bulldozers, diggers, and tractors.

New Zealand's future transport energy requirements can be estimated from the figures in Table 2.0.1, which defines New Zealand's hypothetical demand for liquid fossil fuels in 2040 in two possible scenarios.

Endurance racing has many parallels with practical transport. Consider the highly competitive courier business. Some couriers wear shorts and running shoes and run through their work-days. Time is everything: they have to make all their pickups and deliveries while their customers are open for business. The courier who can't complete their run, every day, risks losing their contract to someone who can. Life is a race. Losing has serious consequences: they are owner-drivers; they mortgage their homes to buy their vans; without a contract they're out of business.

The racing metaphor captures some, but not all, of the essence of New Zealand's transport system. Winning is a team effort involving driver, pit crew, and behind-the-scenes support staff. The racecar must be appropriate for the task, which usually means it must satisfy rules about its capabilities, safety features, and technology. It must be properly managed throughout the race, so it must be driven fast enough to win, but not so fast as to exceed its capabilities, or else it will either crash or break down.

Like a racecar, a short-haul truck or a courier van usually follows a regular route that begins and ends at a single point: the depot. Drivers work closely with dispatchers, who use two-way radios or cellphones to keep drivers informed about pickups and deliveries, minimising backtracking and maximising loads. A fully-loaded truck or van is far more efficient than a half-empty one.

Geography and New Zealand's Transport System

The racing metaphor does not capture the shape of New Zealand's infrastructure. Roads, railways, seaports and airports are finely adapted to New Zealand's isolation, its mountainous terrain, its long, skinny shape, and the availability of imported machinery. In pre-European times, the transport system depended on waka (canoes) and footpaths. European-style ships revolutionised coastal transport, and by the mid-nineteenth century locally-built schooners were regularly carrying freight and passengers around the coast and back and forth across the Tasman Sea. Imported cattle made heavy-duty land transport a practical proposition. A bullock-team could work all day, dragging loads as heavy as ten tonnes or more at speeds up to one kilometre per hour. By the end of the nineteenth century, coal-fired steamships and railways were well-established. Steamships and railways made it far more economical to transport goods over vast distances, but they could never extend their tentacles into every nook and cranny of this craggy land. That job was left for horses, bullocks, and traction engines.

Many highways follow the routes of early bullock tracks, which often followed centuries-old footpaths. Curves have been straightened, bumps and hollows smoothed, bridges have replaced ferries, and today's roads are far wider than Maori footpaths, but their routes have been shaped by centuries of practical experience.

Some parts of the system are more recent. For example, railway lines were established by nineteenth-century surveyors who often faced extreme difficulties. They could not easily convert footpaths and bullock tracks into railways because trains cannot climb steep slopes, so early surveyors were sometimes forced to pioneer new routes. One of the most dramatic examples of their skill and creativity is the central section of the North Island Main Trunk Railway. By the time this project began in earnest, railway engineers knew that New Zealand's rough terrain would require a mountain railway system, with tighter curves than the standard gauge railways then being built in Europe and America. To achieve this tight curvature they reduced the distance between the rails from 1435 mm (*Standard Gauge*) to 1068 mm (*Cape Gauge*), a popular size in British colonies.

Railways

When it comes to moving lots of freight over long distances, trains are more energy-efficient than trucks. A two-person train crew can haul the equivalent of up to forty-five truckloads of freight. With steel wheels running on steel rails, railway vehicles have less friction than rubber-tyred trucks running on tar-sealed roads.

When there is a practical choice of road or rail, some large freight-forwarding companies prefer trains. The *Less-than-Container-Load* (LCL) segment offers an interesting example. LCL shipments consist of just about anything, from pillows to electronic goods to second-hand car parts. Long-distance LCL freight can travel by road or rail. The choice depends mainly on whether the freight-forwarding company has inter-modal depots at both ends of the long-haul run. Inter-modal depots transfer freight between one mode of transport and another, in this case, between trucks and trains.

A pallet-load of freight consigned from Auckland to Christchurch may travel by train. A short-haul or local delivery truck collects the freight and carries it to an inter-modal depot, where it is transferred onto a railway wagon. Late in the afternoon, a shunting engine collects the loaded wagon and hauls it to a shunting yard, where it is coupled into a Wellington-bound freight train. Running overnight, the train reaches Wellington early the following morning. It is broken up and South Island wagons are shunted onto a rail ferry and carried across Cook Strait. At Picton the wagons are assembled into another freight train which is hauled to Christchurch and disassembled. A shunting engine hauls the loaded wagon to a depot, where the pallet is transferred onto a local delivery truck which carries it to its final destination. A pallet that leaves an Auckland warehouse on Monday afternoon will reach Christchurch on Wednesday.

Sometimes Kiwirail doesn't have enough wagons, so the freight-forwarder is forced to send the pallet by truck. It will take exactly the same length of time to reach its destination. However, because trucking is more expensive, the freight-forwarder earns less money.

Auckland to Wellington LCL freight is more likely to travel by road, because few freight-forwarding companies have efficient inter-modal depots in Wellington. Depots such as Mainfreight's Otahuhu LCL operation require special railway sidings so that wagons can be shunted into the depot. Wellington's freight forwarding depots lack the necessary sidings.

Even though Kiwirail is short of rolling stock, and many lines are so dilapidated that trains are restricted to very low speeds to avoid wrecking bridges, embankments and so on, rail accounts for 14.6 percent of total domestic tonne-kilometres. There seems little doubt that upgrading our railway system would shift freight from road to rail. If, tomorrow, we could double the amount of freight carried by rail, I estimate we might reduce total diesel consumption by up to 6.5 percent. That would reduce greenhouse emissions.

This book is not about reducing greenhouse emissions. It is about eliminating them.

Trains are useless without trucks, and although we might shift some freight from one to the other, we need both.

Public Transport

It is often said that better public transport will reduce greenhouse emissions. Regular users of Wellington's electric trains would probably agree that trains get them to and from work far more efficiently than cars. The trains are usually packed to the gunwales, and many Wellingtonians are experts at standing in the aisle of a rickety electric unit with few decent handholds, juggling their morning papers and their umbrellas and not falling over as the train rocks and bucks its way around the harbour. Without the trains, Wellington's motorway would need at least three extra lanes, each way.

Outside peak hours the situation is less clear-cut. A private car almost always carries at least one passenger (the driver), whereas trains and buses sometimes run empty. Cars can sometimes be more energy-efficient than public transport. So, although public transport can reduce greenhouse emissions, it does not eliminate the need for cars.

Road Transport

Even if Kiwirail can fix the railway system and buy more freightcars, New Zealand will still need trucks.

Some routes simply aren't suitable for rail, either because the topography is too rugged or because there is not enough freight. For example, a direct railway between Auckland and Napier was ruled out during early exploratory surveys for the North Island Main Trunk. It was, and may still be, impracticable to build a railway through that rugged landscape. Auckland to Napier trains travel to Palmerston North and then double back through the Manawatu Gorge. A long-haul truck is faster because the road is more direct.

The flexibility of large trucks is often the deciding factor. Industries such as forestry and agriculture rely heavily on road transportation, largely because their needs vary from season to season. A 44-tonne tanker-truck can collect milk from farms that will always be out of the reach of trains. This is also true of logging trucks. We might shift some of this traffic from road to rail, but we'll still need trucks to get the freight from the forest or farm to the nearest railway.

The supermarket industry is a significant road transport user. Big-box supermarkets usually carry enough stock to keep them going for about five or six days. They receive several deliveries per day, and many items are wheeled directly from the dockway to the shelves. The system is designed to minimise travel time from factory or farm to pantry. Without large trucks that can carry freight direct from farm to warehouse to supermarket, our cities would quickly become uninhabitable because the shelves would be stripped bare. New Zealand might reduce diesel consumption by changing the structure of its food distribution system. But the system will always depend on land transport. An effective land transport system requires both roads and railways.

The Practical Requirements

Our economy depends on a wide range of machinery and vehicles. Trucks, trains, planes, ships, vans, helicopters, cranes, bulldozers, diggers. Even cars. They all matter. There's nothing unique about that. It is equally true all over the world.

A carbon-neutral economy will need technologies and energy systems that address this diversity. This book will focus on the largest road vehicles (trucks), as well as the most numerous (cars), along with ships, aircraft, and non-road machinery. The critical factors are payload, operating range, refuelling time, fuel distribution, operating costs, safety, and *Energy Return on Energy Invested* (EROEI).

If an energy technology is to contribute to the economy, it must harness more energy than it consumes. For example, in the process of pumping crude oil out of the ground, transporting it to New Zealand, converting it into petrol and diesel, and transporting finished fuel to service stations, energy companies consume energy. Based on a report by Andrew Barber, of AgriLINK NZ Ltd, New Zealand petrol and diesel contains 5.2 times more energy than the amount consumed by the production and distribution process: The EROEI comes to 5.2.

Researchers argue about the ideal minimum EROEI. However, it seems to me that any form of energy with EROEI greater than five can't be any worse than New Zealand's existing fuels.

Trucks are governed by strict rules about their maximum weight and physical dimensions. These rules ensure they fit under bridges and don't put too much weight on the roads. Truckers charge for heavy freight by the tonne, but bulky freight is charged by the cubic metre or *Cube*. A truck's payload depends on both factors. For heavy freight, its maximum payload is the difference between its unladen (*Tare*) weight, and its maximum loaded (*Gross*) weight. For bulky freight the maximum payload is determined by the height, width, and length of the truck's bodywork.

If a new engine or fuel technology is heavier or bulkier than existing technologies, trucks based on that technology will have smaller payloads. Trucking would become less efficient, and that would ripple through the entire economy. Supermarkets would be forced to pay higher freight rates to keep truckers interested in carrying their goods, and you can bet your teddy-bear they'll pass these extra costs straight on to their customers.

Fuel costs only account for about seven to eleven percent of a trucker's outgoings. The big costs are usually tyres, mortgage payments, and insurance (not necessarily in that order). The mortgage payments and insurance costs depend on the purchase price of the truck, which means that if truckers switch to more expensive trucks that use less fuel, freight costs may rise.

Long-distance truckers generally expect their trucks to go an entire shift, perhaps 650 kilometres, on a single tank of fuel. Short-haul truckers cover less distance per shift, but they too expect good operating range: enough for three or four days of hard work. Refuelling lengthens what is often a long workday: the less time a trucker spends refuelling, the more time they can spend with their families.

Buses and long-distance coaches are governed by the same dimension and weight limits that apply to trucks. Refuelling times, operating range, and running costs have a similar impact on their economics. If a technology works for trucks, it should also work for buses.

Boats and aircraft are governed by the same technological constraints as those that govern road transport. The difference is a matter of emphasis. An aircraft's payload is limited by the amount of weight it can lift off the ground: *The Maximum Take-off Weight*. A boat's maximum payload is determined mainly by stability considerations: An overloaded boat may not actually sink, but it is more likely to capsize in rough weather. In both cases, the size and weight of engines and fuel tanks can affect more than just the payload. It may not be feasible to design an aircraft, or even a boat, using engine or fuel technology that is significantly heavier, or bulkier, than present-day technology. An aircraft is useless if its fuel or engine is so heavy that it cannot get off the ground.

On the other hand, there’s no technical reason why cars cannot be several times heavier than present-day models, if that is what it takes to carbon-neutralise them. If the maximum loaded (*Gross*) weight exceeds 3.5 tonnes, then under New Zealand transport rules they would be classified as heavy vehicles. But, if four or five tonne cars are better for the planet than two-tonne cars, there’s no reason we should not change the rules.

There’s little point investigating the impact of new technologies on our railway system. The modern electric railway is universally acknowledged as the most energy-efficient land transport system ever invented, and it was invented a very long time ago: The first electric freight trains entered service in 1895. There is no technical reason we couldn’t electrify our entire railway system and carbon-neutralise our electricity supply. It’s a matter of making it an economic priority. Besides, our railways account for less than two percent New Zealand’s total diesel consumption, and yet they account for almost fifteen percent of our total freight on a tonne-kilometre basis. Kiwirail’s contribution to New Zealand’s greenhouse emissions is negligible, and when the time is right, they’ll have no trouble eliminating their direct greenhouse emissions altogether. That’s why this book will concentrate on modes of transport for which climate-friendly solutions are less obvious.

Unfortunately, we can’t take it for granted that a technology that works for trucks will also work for machinery such as graders, diggers, and tractors. Non-transport fuel users may be interested in factors that don’t affect truckers. For example, many of them have to carry fuel to their machines. This is easier with diesel than petrol, because diesel engines need less fuel, and because diesel fuel is safer than petrol. We must keep in mind that if a new technology works for road vehicles, but not for construction and agricultural machinery, we may be forced to continue importing fossil diesel, even though we no longer use it for transport.

Future Demand

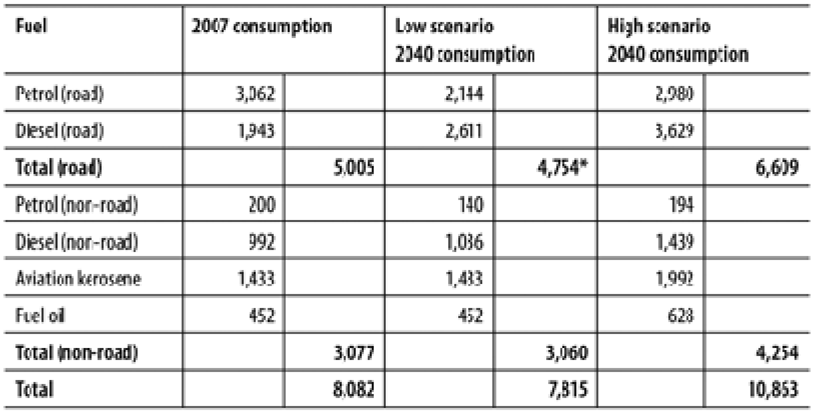
Between 1990 and 2007, New Zealand’s liquid fuel consumption grew by an average of 2.5 percent per year. This trend is very unlikely to continue. It is fashionable to emphasise fuel efficiency. Many New Zealanders support investment in better public transport, improved railways, and increased coastal shipping. This ought to reduce fuel consumption.

It is also important to consider the trend from petrol to diesel. Between 1974 and 2006, our diesel consumption increased by 184 percent, while our petrol consumption grew 46 percent. Back in the 1960s, just about everything on our roads ran on petrol. Diesel-powered logging trucks were becoming common and most earthmoving equipment ran on diesel, as did the largest farm tractors. But medium-sized trucks used petrol, and in spite of the fire hazard, so did many small tractors. Now, small diesel tractors have become ubiquitous, and medium-sized trucks are almost exclusively powered by diesel. With diesel cars now as practical and exciting as petrol ones, there’s no reason to think this trend won’t continue.

Rather than try to guess exactly how much energy New Zealand will need, this book looks at two visions of the future. In the *Low Scenario*, New Zealand’s 2040 fuel consumption would be essentially the same as its 2007 consumption. In the *High Scenario*, fuel consumption would grow by an average of one percent per year.

These scenarios are conservative. It is possible that by 2040, New Zealand’s economy may need less fuel than it did in 2007. But it is better to be conservative, and be pleasantly surprised that New Zealand needs less fuel; than try to re-engineer the economy only to discover the project was never viable because demand was underestimated.

Table 2.0.1: Projected liquid fuel consumption for New Zealand (millions of litres).



Fuel	2007 consumption		Low scenario 2040 consumption		High scenario 2040 consumption	
Petrol (road)	3,062		2,144		2,980	
Diesel (road)	1,943		2,611		3,629	
Total (road)		**5,005**		**4,754***		**6,609**
Petrol (non-road)	200		140		194	
Diesel (non-road)	992		1,036		1,439	
Aviation kerosene	1,433		1,433		1,992	
Fuel oil	452		452		628	
Total (non-road)		**3,077**		**3,060**		**4,254**
Total		**8,082**		**7,815**		**10,853**

**** Some totals do not balance because of rounding.***

International transport accounts for about seventy-two percent of our aviation fuel, twenty-two percent of our fuel oil, and a sniff (two percent) of diesel. Although fuel used for international transport does not contribute to New Zealand’s domestic greenhouse emissions, it is vital to the economy. We must be able to convince foreign consumers that when they visit New Zealand for a holiday, or when they purchase New Zealand products, they will not exacerbate climate change. Our story will be a great deal more credible if we can honestly tell them every aircraft or ship that buys fuel in New Zealand buys truly carbon-neutral fuel.

* * Table of Contents * *

Box 2.1: The World War II Gas Producer

When wartime petrol shortages threatened to clamp New Zealand's mobility, our grandfathers mounted gas producers on their cars and ran them on coal or charcoal.

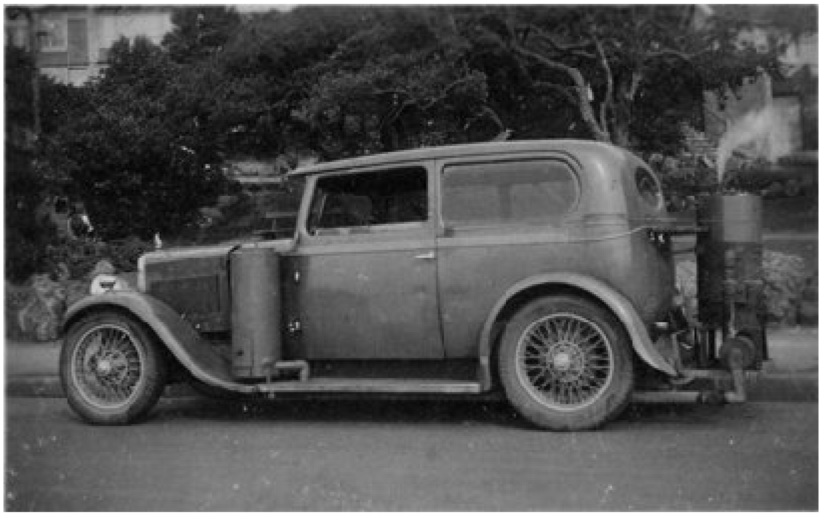
World War II gas producers evolved from massive nineteenth-century stationary systems such as the Cable Gas Producer manufactured at Wellington's Lion Foundry. A 1907 article in *Progress* magazine raved about this highly efficient machine, which could power a 44 horsepower internal combustion engine for an entire nine-hour workday using only three sacks of coke.

Nineteenth-century gas producers were far too big and heavy for road vehicles, but they were seen as a potential alternative to imported oil. European engineers refined and improved the technology, and by the outbreak of World War II, gas producers were small and light enough for trucks and large cars. They become an essential feature of road transport in countries without indigenous crude oil. In Sweden, for example, 70,000 cars, trucks, and tractors were fitted with gas producers by 1942.

Some manufacturers distributed gas producers through vehicle dealer networks. For example, General Motors dealers in New Zealand sold the NASCO. However, many designs were well within the capabilities of small general engineering companies, and locally-made gas producers become common in New Zealand.

One such design was developed by a committee of government engineers convened by Dan Sullivan, the Minister of Supply. The business end of the New Zealand *Emergency Producer* was the four foot tall by eighteen inch diameter (120 cm x 46 cm) cylindrical gasifier. Fuel went through an airtight door in the top, air went through an intake low down on one side, and *Producer Gas* came out of a pipe about halfway up the other side.

Figure 2.1.1



Arthur Slocombe's Alvis Silver Eagle at Oriental Bay in 1942. Slocombe was an engineer. He built the gas producer from plans developed for the New Zealand Ministry of Supply, and described in a booklet called: Producer Gas: Emergency use for automotive purposes. (Photo by courtesy of Peter Slocombe.)

Raw producer gas contained a lot of dust that could wreck the inside of an engine, which is why it was forced to swirl its way through a four foot long by ten inch diameter (120 cm x 25 cm) cylinder optimistically called a Cyclone, which removed some of the dust. A filter got rid of more dust, soot, and crud.

An efficient driver could clean the whole setup, gasifier, cyclone, and filter, in about half an hour; a filthy job, but better than walking.

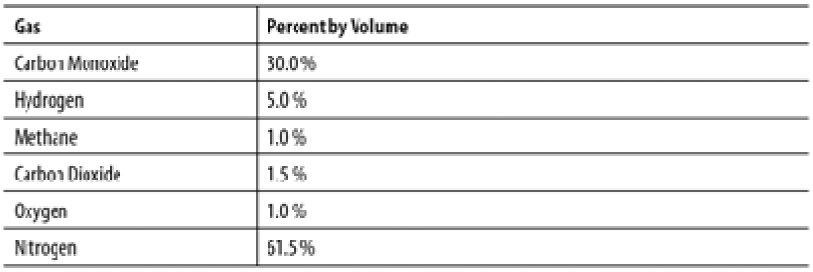
The active ingredient in government-sanctioned producer gas was carbon monoxide. Carbon monoxide will burn, releasing heat as it combines with oxygen to form carbon dioxide. It's a useful fuel gas, though not as good as methane or hydrogen.

Fancy coke-burning gasifiers mixed a little steam into their air supply. The gas from these high-faluting producers contained hydrogen, which adds considerable oomph. However, the Minister of Supply's technical committee was apparently *of the opinion that the extra equipment and complications involved in the use of water to obtain a gas of higher calorific value is not justified by the practical result obtained*[6].

Starting a gas producer was easier than starting a steam engine. The recommended technique was to start the engine on petrol, and then set fire to the fuel in the gas producer, adjusting the engine's fuel mixing valve to make the engine draw air through the producer. A good gas producer would be up and running within a minute or so, and the government committee reckoned the starting procedure required less than a pint (600 ml) of petrol. That was fine, if you could get petrol. Another trick was to disconnect the outlet pipe and use an old vacuum cleaner to suck air through the producer. After a few minutes, you could fire up the engine on producer gas. Or at least, you could if you hadn't expired during the warm-up process. In Sweden–home of the Electrolux and winters so cold even a Swede thinks twice about going outside in the morning–they had several fatalities, apparently because of a local habit of starting cars and trucks inside garages or barns. The vacuum cleaner would quickly fill a small building with carbon monoxide, which happens to be poisonous.

The car to have in those days was the Buick. With a five-litre straight eight capable of about a hundred and forty horsepower on petrol and at least seventy on producer gas, a well-tuned gas-producing Buick could do 80 miles per hour (128 kph) on the flat. So I'm told. Like this book, the Minister of Supply's technical committee was not interested in such frivolity. They installed their prototype on a 60 horsepower 1936 Ford truck. The well-used but still-perky V8 made thirty horsepower on producer gas, enough to push the truck along at forty miles per hour (64 kph), fully loaded with two and a half tonnes of steel rails which brought its all-up weight to more than five and a quarter tonnes. On a trip from Wellington to Palmerston North via Shannon, and back via the Rimutakas, its total running time was 6 hours and 42 minutes for the 348-kilometre journey, an average of 52 kilometres per hour.

Table 2.1.1: Typical composition of producer gas.



Gas	Percent by Volume
Carbon Monoxide	30.0%
Hydrogen	5.0 %
Methane	1.0 %
Carbon Dioxide	1.5 %
Oxygen	1.0 %
Nitrogen	61.5 %

* * Table of Contents * *

Chapter 3: Internal Combustion Engines

Efforts to reduce smog do not affect the choice of carbon-neutral engine technology.

Smog-causing emissions from today's petrol and diesel engines are negligible. Further improvement is very likely, if governments introduce better anti-smog regulations.

Ships and non-road equipment and vehicles can use anti-smog technology developed for road vehicles.

Future aviation engines can be expected to produce less smog than today's aircraft engines.

One of the most interesting aspects of Audi and Peugeot's diesel sportscars is that they do not produce vast clouds of smoke.

Diesel-powered motorsport is not new. Weekend TV sometimes shows full-sized trucks racing around tracks barely wide enough for Minis to run two abreast without trading paint, and YouTube has plenty of clips of hopped-up diesel tractors dragging blocks of concrete along improvised drag-strips. Thick clouds of exhaust smoke create the impression that the object of diesel racing is find out who can make the most pollution: It looks like an industrial variation of the traditional burnout contest; in which drag-racing petrolheads compete for the dubious honour of converting their tyres into the biggest, thickest, most eye-watering cloud of smoke.

Le Mans diesels are different. Even under hard acceleration there's no hint of exhaust smoke because they have all the latest anti-smog equipment. Like many road-going diesel cars and trucks, they satisfy tough anti-smog regulations that have forced car and truck manufacturers to dramatically clean up their tailpipes. Between 1995 and 2004, road passenger transport in Europe increased by sixteen percent while road freight increased thirty-five percent. And yet over the same period, transport-related emissions of ozone-causing chemicals fell thirty-six percent while particulate and particulate-causing emissions fell twenty-five percent[7]. Ozone is desirable in the upper atmosphere, but at lower levels it is a toxic pollutant. Particulates are tiny bits of crud that float around in the air like dust motes.

The European car and truck fleet still contains a great many vehicles that do not satisfy the latest anti-smog rules. As these older vehicles are replaced, transport-related smog in Europe should continue to fall.

If we are going to replace fossil fuels with something else, we cannot ignore smog. According to NIWA, transport is the main cause of smog in Auckland, though solid fuels such as wood seem to be the main cause of smog in smaller cities and towns.

It is tempting to focus on vehicles that produce no emissions. This raises an interesting question: Is there such a thing as a zero-emission vehicle?

Tyre, Brake, and Clutch Emissions

A recent World Health Organisation report points out that exhaust emissions are not the only cause of pollution: *Other emissions related to road transport (such as those from resuspended road dust, and wear of tyres and brake linings) are the most important source of the coarse fraction of [particulate matter]…* The report goes on to show that European emission rules in 2005 were so effective that new road vehicles create almost as much particle pollution from their tyres, brakes, clutches, and from kicking up road dust, as they do from their exhaust pipes[8]. It's not just boy racers who leave bits of tyres and brake-pad on the road. These components gradually wear out, which is why they are checked during warrant of fitness inspections. Some of the material that wears away from brake-pads floats around in the air in the form of fine dust. The same thing happens to tyre treads. Even after it settles on the road it can still cause pollution because passing vehicles stir it up.

All road vehicles have tyres, and according to the World Health Organisation, tyre and road emissions account for about a quarter of the total particle emissions from vehicles that meet the 2005 European emissions regulations.

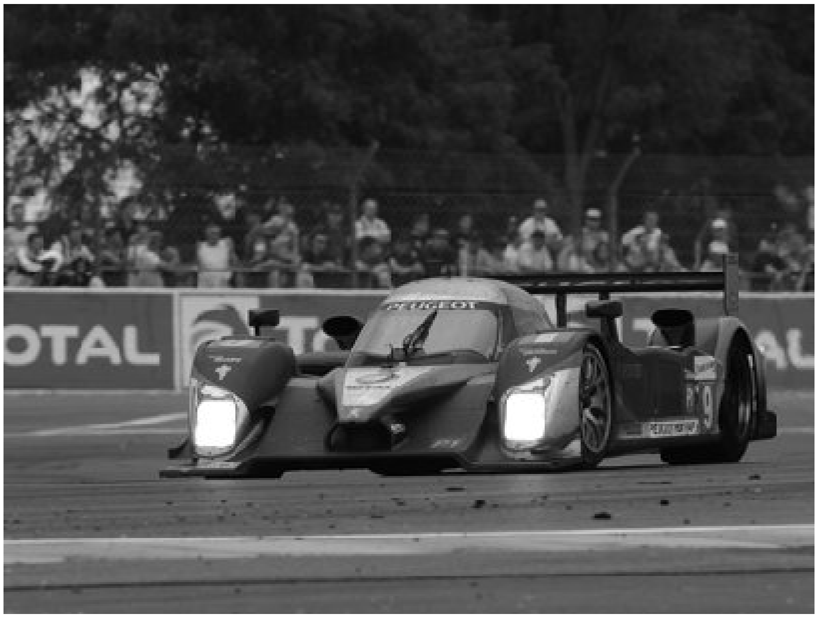
Hybrid-hydraulic and hybrid-electric transmission systems will knock a dent in the roughly 15 percent of particle emissions that come from clutches and brakes. All future vehicles are likely to have hybrid transmission systems, whether they run on batteries, hydrogen, diesel, petrol, or ethanol. No matter what type of engine drives our future transport system, we can expect road vehicles to create less pollution from transmission and braking systems.

Engines Should Not Make Smog

There is no law of nature that says internal combustion engines must produce smog. Although the exhaust from early petrol and diesel engines had plenty of smog-producing chemicals, this was merely a sign that things were not right. The exhaust from an internal combustion engine running on conventional fuels should contain carbon dioxide, water, nitrogen, and normal atmospheric trace gases. Nothing else. The carbon dioxide and water come from combustion, which is a chemical reaction between oxygen from the air, and carbon and hydrogen from the fuel. There'll be nitrogen in the exhaust because air is mostly nitrogen. This should not participate in the chemical reaction; it should go straight through the engine. The same goes for trace inert gases such as argon. If the fuel contains impurities, or if the engine's design is not good enough, or if the engine is badly adjusted or worn-out, the exhaust will contain many other chemicals. Some of these undesirable chemicals cause smog.

Some kinds of smog can be fixed by cleaning up the fuel, and other kinds of smog can be fixed by improving the engines. And some smog can eliminated through better maintenance.

Figure 3.0.1



A diesel-powered Peugeot 908 at the Twenty-Four Hours of Le Mans in June 2009. The black lumps on the track are pieces of rubber from racecar tyres. Note the lack of exhaust smoke. (Photo: Copyright Agence DPPI et Midi, via Peugeot Sport.)

Better Fuel Cuts Smog

Improving the fuel can be as important as improving the vehicles. For example, in early 2006 New Zealand adopted low-sulphur diesel, a vital step toward the introduction of practically smog-free diesel vehicles. Sulphur is a common impurity in most fossil fuels. It comes from the raw material, crude oil, and it doesn't hurt old-fashioned diesel engines, but it damages urban air quality. When an engine burns sulphurous fuel it produces oxides of sulphur, collectively, and very appropriately, known as SOx. In the atmosphere these gases combine with water to form sulphuric acid, which is one of the acids in *Acid Rain*. Eliminating sulphur from automotive fuels takes the SOx out of automotive exhausts.

Low-sulphur diesel has a second important benefit: it opens the way for clean-diesel engines. SOx ruin the anti-smog equipment that strips nitrogen oxides (NOx) from exhaust gases. Nitrogen oxides are formed when the temperature and pressure inside an engine become so high that normally-inert nitrogen burns, combining chemically with oxygen. NOx emissions contribute to smog and acid rain. Today's clean-diesel cars and trucks are almost entirely smog-free, but they require diesel that contains little or no sulphur.

Early anti-smog regulations focused on unburnt hydrocarbons, carbon monoxide, oxides of nitrogen and sulphur, and soot. Until the late twentieth century these were considered the main smog-causing emissions from internal combustion engines. It is now known that vehicle emissions are more complex than that. For example, ethanol engines produce aldehydes, a group of toxic, oxygenated hydrocarbon compounds. As well as carbon and hydrogen, aldehydes contain oxygen. Pollutants such as aldehydes are sometimes called *Unregulated Emissions*, because they are not covered by present-day anti-smog rules. Some researchers argue that aldehyde emissions are not as bad as particle emissions from diesel exhausts. Certainly, fine particles create a more serious health hazard, but this does not mean that air quality regulations can ignore aldehydes.

Petrol and Diesel Engines

Modern piston engines, diesel or petrol, are so clean that they are no longer the principle source of smog-related emissions, especially in European cities, but Europe has not beaten its urban air quality problems. Other sources of air pollution still need to be cleaned up or phased out, including older road vehicles. And authorities have not relaxed their efforts to cut emissions from road transport. Europe recently adopted even tougher rules. While Europe was developing its latest anti-smog regulations, Japanese and American authorities have taken the lead, with emissions rules far tougher than the current European rules.

The outlook for internal combustion engines seems promising. To satisfy tough anti-smog regulations, most new vehicles have equipment that removes harmful exhaust emissions. For example, filters remove fine particles from the exhaust of most new diesel vehicles. (Exhaust filters are especially important because fine particles cause more severe health effects than coarse particles from tyres, brakes and clutches.)

Diesel soot contains a type of particle known as *Black Carbon*, which is a potent greenhouse warming agent. Most atmospheric black carbon comes from the human-induced and natural burning of forest and savannah. Solid-fuelled residential fires and stoves, and industrial boilers, also produce lots of it.

The problem of black carbon and smog explains why wood-burning steam engines will never make a comeback. In the late nineteenth and early twentieth centuries, wood-burning steam locomotives powered many private railways in New Zealand, notably the 134 km Wellington-Manawatu Railway from Wellington to Longburn (1886–1908), including the present-day Johnsonville Line, and the 83 km Taupo Totara Timber Company railway between Mokai (near Taupo) and Putaruru (1905–45). Wood-burning steam engines, like domestic wood fires, produce lots of soot. So, although wood is a biofuel, the wood-fired steam train is not a practical solution to anthropogenic climate change. If anything, it would worsen the problem and, at the same time, exacerbate smog.

About twenty-four percent of global black carbon pollution comes from internal combustion engines, especially diesels without exhaust treatment systems. A study by Mark Z. Jacobson, of Stanford University, suggests that over the course of twenty years, one tonne of diesel soot warms the global climate as much as 2,530 tonnes of carbon dioxide[9]. Jacobson's findings are preliminary, and more research will be necessary before the role of black carbon can be properly understood. But, fortunately, particle filters eliminate this problem. Today's diesel vehicles cause significantly less global warming than petrol vehicles.

We can expect future diesels to be even cleaner. Heavy vehicles sold in Europe after about 2014 will be subject to the Euro VI specifications, which allow only half the level of soot permitted by the Euro V rules. Further improvements are possible.

A recent development illustrates the practical potential. Simply by heating diesel fuel before injecting it into the cylinders, George Anitescu and Lawrence L. Tavlarides (of Syracuse University, New York), and their colleagues eliminated soot and NOx formation in a diesel engine. This simple modification transformed the test engine into a type that blends the best features of diesel and petrol engines: An *Advanced Combustion Engine* (Box 3.1). The researchers call their system Supercritical Fuel Injection. Engines with this technology would easily satisfy existing and proposed anti-smog rules without exhaust treatment systems, and they would also be a little more efficient than today's engines.

Even without breakthrough ideas such as supercritical fuel injection, diesel engines are getting cleaner. For example, Daimler recently launched a low-emission bus that satisfies the toughest current European standards without a particle filter. The previous model required a particle filter to satisfy the same regulations[10].

There is no reason why ships and diesel trains cannot achieve smokestack cleanliness at least as good as road vehicles. Most ships have diesel engines which can use the same anti-smog technologies that have been applied to truck and car engines. Some manufacturers of large marine engines are already getting on with it.

Gas Turbine Engines

Gas turbine engines are another matter. The gas turbine is the basis of almost all aircraft engines, and it is also used in high-performance heavy vehicles such as tanks and some naval ships. In principle, gas turbine engines can run on just about anything, but the overwhelming majority of aircraft engines burn kerosene, and marine gas turbines usually burn diesel.

As with piston engines, SOx emissions from gas turbines can be eliminated by removing sulphur from the fuel.

Researchers are only just beginning to look for ways to cut NOx emissions from gas turbines. For example, NASA recently launched its *Subsonic Fixed Wing Project*, which aims to develop new technology for jet airliners. One of their main objectives is to slash aircraft emissions. If they achieve their goals, NOx emissions from airliners entering service during the 2020s will be seventy-five percent lower than those of comparable present-day aircraft[11].

Soot emissions from aircraft engines might be reduced by improving the engines, and perhaps by eliminating a class of hydrocarbons known as Aromatics from the fuel. Unfortunately, this has implications for synthetic rubber components used in fuel systems. There have been concerns that aromatic-free fuels may trigger fuel leaks. Recent alternative fuel test flights are helping aviation engineers learn about aromatic-free kerosene. Many of these publicity flights used *Hydrotreated Renewable* (HR) kerosene (Box 16.1). Others used *Gas-to-Liquid* (GTL) synthetic kerosene, which is identical to *Biomass Gasification and Fischer-Tropsch* (BGFT) kerosene (Chapter 12). These synthetic fuels are practically free of aromatic hydrocarbons.

Synthetic Fuels

Intense competition between manufacturers continues to improve the performance of internal combustion engines and their fuels. Recent research is beginning to suggest the best way forward is to optimise the fuel and the engines to suit each other’s characteristics, instead of trying to design engines to run on whatever fuel happens to be available. Liquid fuels contain hundreds of different hydrocarbons. The exact recipe depends on the composition of the crude oil from which the fuel is made. This varies from oilfield to oilfield. Fuel manufacturers have a better chance of controlling the composition of synthetic fuels. Engines optimised to run on specially tailored fuels should be significantly cleaner than those designed to run on whatever the oil companies pump out of the ground.

Selecting Carbon-Neutral Technologies

New Zealand’s choice of carbon-neutral technology will not be influenced by potential smog emissions. There’s no significant difference between the technological options.

New Zealand must adopt anti-smog legislation equivalent to that of Europe or the USA. If it doesn’t, there’ll be nothing to stop vehicle importers buying cars and trucks from countries without emissions regulations, or importing cheap versions without anti-smog equipment. Low emission technology costs money. No manufacturer will install it unless their competitors do the same.

There are good reasons to tighten anti-smog regulations. The existing rules do not cover a range of pollutants such as aldehydes. There is growing evidence that ultra-fine particle emissions from diesels, and from direct-injected petrol engines, pose a health hazard. Tighter regulations will encourage vehicle and fuel manufacturers to continue improving their products.

With these provisos, we can be confident that whether New Zealand goes with batteries, or hydrogen fuel-cells, or advanced biofuels, or whether a technological kaleidoscope is the best way to go, New Zealand’s air quality should improve as time goes on.

* * Table of Contents * *

Box 3.1: Advanced Combustion Engines

Several manufacturers are investigating new types of engines that might combine the advantages of petrol and diesel engines. Traditional petrol engines burn their fuel very smoothly, so they produce very little soot unless they are worn-out or badly adjusted. The diesel engine is more efficient because of its high compression ratio and because its intake system does not need a butterfly valve, or throttle, for speed control. But traditional diesels make NOx and soot.

Marketing and public relations departments have coined new buzzwords for newly-invented engines. Volkswagen has CCS (Combined Combustion System) and GCI (Gasoline Compression Ignition); Daimler had CHHC (Combined Homogeneous Heterogeneous Combustion), but they took mercy on motoring journalists and renamed it the Diesotto (A contraction of Diesel and Otto, the German engineers associated with the engines it is designed to replace). Cummins, Caterpillar, General Motors and Honda are also experimenting with advanced combustion. Cummins has reportedly claimed advanced combustion engines, with other improvements, will achieve thermal efficiency close to sixty percent by 2015, which, if it comes true, would mean they'll get thirty-three percent more work out of a litre of diesel than present-day truck engines[12].

Advanced combustion engines exploit a principle that has been used for decades in miniature engines for model aircraft and boats, known as *Homogenous Charge Compression Ignition* (HCCI). Like petrol engines, HCCI engines inhale a mixture of fuel and air. This is squashed so hard the intense pressure and heat set fire to it. Although this is sometimes called *Compression Ignition*, it is quite different from what happens inside a diesel. A diesel inhales air, and then squashes it, raising its temperature and pressure. Then the fuel injection system squirts fuel directly into the combustion chamber. The fuel ignites shortly after leaving the fuel injector, like a flame thrower squirting fire. In the HCCI engine, the fuel is evenly spread throughout the combustion chamber. It catches fire in numerous places pretty-much simultaneously.

Some writers say there is no way to control the exact time of ignition in an HCCI engine, but this is not entirely true. The ignition timing in miniature engines is controlled by adjusting the compression ratio. Usually the roof of the combustion chamber can slide up and down, controlled by a screw on top of the engine. Increasing the compression ratio makes the fuel ignite earlier in the operating cycle.

This does not provide the very precise control that can be achieved in petrol and diesel engines. Ignition in a petrol engine is triggered by an electric spark jumping across the spark plug. In the diesel, ignition starts shortly after the injector begins squirting fuel into the cylinder. Both methods give very precise control of the combustion process.

Most advanced combustion engines morph between different modes of combustion. One type uses spark ignition when it is heavily loaded. This is often called Controlled Auto-Ignition (CAI): It's a petrol engine when it is working hard; and a CAI engine when it is loafing. Some advanced combustion engines operate in diesel mode for heavy loads, and HCCI mode for light and medium loads.

Although the names HCCI and CAI seem interchangeable, it is handy to reserve one for advanced combustion engines that have spark plugs (CAI), and another for those that do not (HCCI).

Supercritical fuel injection may simplify the control of ignition timing in HCCI engines. In this system, heated fuel is injected into the combustion chamber. Because it is so hot, the fuel mixes almost instantaneously, forming a homogenous fuel-air mixture before it starts burning. As in a diesel, ignition timing is controlled by the fuel injection system. The engine does not need to morph into diesel or petrol mode under heavy load. Most importantly, published test results show that the system eliminates the very high temperature and pressure at the start of combustion in conventional compression-ignition engines. High temperature and pressure causes NOx: Supercritical fuel injection eliminates NOx[13].

An engine with supercritical fuel injection can be designed to run on petrol, diesel, kerosene, ethanol, naphtha, or any other liquid fuel. It does not need a high compression ratio, because the fuel is so hot it readily ignites at lower temperature and pressure. The system can be applied to small, lightweight, high-revving engines for motorcycles and outboard motors, just as easily as it can be applied to large, high-efficiency, heavy-duty engines for trucks, trains and ships. It's difficult to make very small diesels perform as well as petrol engines, because their intake and exhaust systems are too small to cope with the large air flow necessary for high performance.

Supercritical fuel injection is a simple technology that ought to reach commercialisation within a decade or so. Engines with this technology could replace conventional petrol and diesel engines. The potential payoffs include: better fuel efficiency (about ten percent for high-compression truck and large car engines); no need for high-octane fuel; and practically zero NOx and soot without exhaust treatment.

* * Table of Contents * *

Chapter 4: Battery Vehicles

Battery vehicles are unsuitable for almost all non-road applications.

They are also unsuitable for heavy-duty road transport.

Small battery trucks and vans may be suitable for short-range low-speed applications such as local deliveries in highly congested areas.

The cost of battery replacement dominates battery-vehicle running costs. Modern battery vehicles have lithium-ion batteries, which have a life expectancy of seven to ten years, whether they are used or not.

NZ told to embrace electric car, screamed the headline under a photo of a topless red coupé[14]. Capable of accelerating from zero to a hundred kph in less than four seconds, the pavement-scorching Tesla Roadster had captured the imagination of a Dominion Post reporter covering the Energy Efficiency and Conservation Authority's 2008 *Biofuels and Electric Cars Conference*. At that time, Tesla Motors had pre-sold their entire production of 2008 models and were taking orders for 2009 editions at $US 109,000 a pop ($NZ 160,230). The conference had been told that *New Zealand would make a wonderful poster child for electric car use*[15], but we'd have to be quick or we'd miss out. It looked more like a car advertisement than a newspaper story.

The Tesla Roadster flamboyantly demonstrates the state-of-the-art of battery-electric-vehicle (BEV) design, but it's not alone. Specialist manufacturers around the world are marketing a wide range of battery vehicles, from sportscars to people-carriers and from miniature vans to medium-sized trucks. They are the obvious low-emission vehicles. They lack exhaust pipes so they produce no direct greenhouse emissions. A battery vehicle has no clutch, so it doesn't spray little bits of clutch-plate onto the street. Its only direct contribution to urban smog comes from its tyres and brakes. It's quite likely that asphalt-ripping battery-burners kick up more particle pollution from the road, and from their tyres, than late twentieth-century road vehicles; but their regenerative braking systems produce less pollution than those of conventional cars and trucks.

Batteries and electric motors are used in several other interesting technologies, such as hydrogen fuel-cell vehicles and some hybrids. These vehicles are more complex than battery vehicles, which is why this part of the book begins with a survey of the current state of battery-electric technology.

Nineteenth-Century Electric Transportation

The electric motor predates the modern internal combustion engine. Michael Faraday demonstrated its basic principle in 1821, more than thirty years before the invention of the petrol engine (1854), and over seventy years before the diesel (1892).

Horses dominated urban transport in Faraday's day, but by the mid-nineteenth century the steam train was beginning to make its mark. Until that time, urban growth had been limited by the practicalities of transportation. Steam railways made it easier to quickly transport food across vast distances, which in turn facilitated the rapid growth of large urban centres. *...America's urban population swelled by thirty million souls between 1800 and 1900. These new citizens needed to be fed, clothed, and sheltered using materials delivered by horse. ...despite the fact that cities were expanding outward, the tidal wave of new residents sent density levels soaring; New York's rose from 39,183 per square mile in 1800 to 90,366 per square mile in 1900. Greater human crowding meant greater horse crowding as well, and problems that might have been tolerable in a sparsely populated rural region became unbearable in a densely packed urban one...*[16] By the late nineteenth century the streets of many major cities were filthy bogs of horse manure, and their air was filled with toxic smog from all those steam engines. The electric motor offered a potential solution. After numerous experiments the first successful electric tram débuted in Richmond, Virginia in 1888. Seven years later, the first electric mainline railway locomotives entered service on the outskirts of Baltimore.

Electric trains and trams could reduce smog, but they could not reduce the need for horses. The more the cities grew, the more they needed short-range flexible transportation to link railway stations with shops, hotels, apartments, and workplaces. In his social history of the USA, J.C. Furnas wrote: *...It is difficult for those reared after the automobile ousted the horse to realize how excrement thus pervaded the outdoors of the nineteenth-century city, making it a sort of equine latrine. Cobblestone pavement kept sweeping up hopeless even when* *tried. The English sparrows imported in 1850 to eat caterpillars flourished on the stuff, but even their population explosion made no headway against the problem. It dried in the summer sun to become high-flavored dust blowing into mouth and lungs. In wet weather it incorporated into the mud that was tracked everywhere, fouling the bottoms of women pedestrians' long skirts, gradually impregnating the straw on the floor of the omnibus until the passengers might as well have sat with their feet in a horse stall needing cleaning…*[17]

Battery-powered cars were soon popular among well-to-do urbanites and they were not displaced by petrol cars until after World War I.

Figure 4.0.1

The 1918 Rauch & Lang battery car: "A dignified, perfect vehicle for town use". The front compartment (where a conventional horseless carriage would have an engine) is packed with batteries, as is the compartment behind the cabin (inset). Operating range, 58 km; top speed, 32 kph. (Photo by the author, with thanks to Southward Car Museum.)

Many New Zealand cities were not even imagined until after 1850 and they have never been as densely populated as their American and European counterparts, but even here, battery vehicles roamed urban streets until the early twentieth century.

The Electric Motor Killed the Steam Train

Steam locomotives were admirable load-haulers but their inefficiency left them vulnerable to competition. Solid-fuelled steamers were soon displaced by oil-burners because of the difficulties of handling wood or coal. But even oil-burners could not compete with new technology. For the same workload, an oil-burning steamer consumes a lot more oil than a diesel. And of course, a diesel makes far less smoke.

Today's "diesel" railway locomotives are actually diesel-electrics. The diesel engine drives an electric generator, which in turn drives one or more electric *Traction Motors*. Early locomotive designers tried other systems, such as mechanical gearboxes similar to those in cars and trucks, but in those days only the diesel-electric system was rugged enough for heavy-duty rail haulage. Somewhat perversely, although the internal combustion engine wrested control of road transport from battery-electrics, the electric motor facilitated the internal combustion engine's dominance of many rail networks, including those of the USA, Australia, and New Zealand.

European railways are also dominated by electric power, but European trains are often pure electrics, like the heavy-duty locomotives that have been hauling trains across New Zealand's mountainous North Island Main

Trunk Railway for the past twenty years.

The Benefits of Electric Motors

Electric motors work superbly in everything from electric screwdrivers and golf-carts, to trucks, trains, and ships, because of their small size, high starting torque, and good efficiency. They also allow automotive engineers to design *Regenerative Braking systems*, which boost operating range.

Light and Compact

Wellington's electric multiple unit trains illustrate how tiny these motors can be. For example, each of the 1988-vintage units is driven by four 100-kilowatt traction motors tucked inside the bogies (The swivelling frames underneath the carriages that hold the wheels, axles, and suspension). There's no chance of cramming heavy-duty diesel engines into the bogies. Some of Auckland's diesel multiple units have special engine compartments inside the driving carriage. Others have flat under-floor engines mounted between, not inside, the bogies.

Electric traction motors are very light. The Tesla Roadster's bicycle-helmet-sized 185-kilowatt motor weighs about 53 kilograms, less than a third the weight of a comparable petrol engine.

High Starting Torque

Unlike petrol and diesel engines, electric motors can pull hard from a standing start. Michael Faraday demonstrated this with his laboratory motor. When he dangled a wire near a magnet and shoved electricity through it, the wire would move. To exploit this principle, motor designers mount either a coil of wire, or sometimes a magnet, onto a shaft which can rotate relative to the motor's frame. This rotating assembly is called the rotor: If it has a coil, there's a magnet on the frame; If it has a magnet, the frame has a coil. But don't be surprised if you tear apart an electric motor and find coils on both rotor and frame. Many motors use electromagnets, which are coils of wire.

Faraday's experiment showed that the rotor feels a strong force even when it's not moving. In technical jargon, an electric motor has a high starting torque. Imagine what happens inside a locomotive traction motor when the driver turns on the power. Electricity surges through the internal wiring. This forces the shaft to rotate. The shaft drives the wheels, and unless they slip, the train starts moving as soon as the rotor starts turning. All the driver has to do is switch on the power. It's a lot simpler than getting underway in a car with a manual gearbox. If you don't have enough revs, or if you let the clutch out too quickly, the engine will stall. Petrol and diesel engines can't pull from a standing start: They produce zero torque at zero revs, and not very much when they're idling.

The electric motor's high starting torque is an asset in almost anything with wheels. A heavy truck needs lots of low-speed grunt to get it moving. The smooth-starting electric traction motor is just the thing, especially for heavy vehicles that do lots of stop-start work such as rubbish trucks and buses.

Low-speed torque leads to snappy acceleration. The Tesla Roadster gets from zero to a hundred kph in 3.9 seconds, about as quick as the Porsche Carrera GT, which is powered by a 5.7-litre, 450-kilowatt, ten-cylinder engine.

Highly Efficient

Electric motors are considerably more efficient than internal combustion engines. A typical traction motor is up to ninety-five percent efficient. This means it consumes a hundred kilowatt-hours of electricity to do ninety-five kilowatt-hours of work. The other five kilowatt-hours is converted into heat. If that sounds wasteful, compare it with a petrol engine. A 100-kilowatt petrol engine running flat-out for an hour will do 100 kilowatt-hours of work and produce at least 233 kilowatt-hours of heat. It will drink enough petrol to supply more than 333 kilowatt-hours of energy: In mathematical terms, it's less than thirty percent efficient. That's why it gets so hot inside a V8 Supercar: Pumping out 475 kilowatts, their engines produce at least 1,100 kilowatts of heat. This is equivalent to more than 458 large domestic heaters running full-bore, though you'd never fit 458 heaters under the bonnet of a Holden Commodore. A V8 Supercar driver spends their workday riding behind a heat source big enough to keep a Central Otago township cosy and warm in the middle of an Antarctic southerly.

Like any other type of motor, electric motors are most efficient only under ideal conditions. Generally, they are most efficient at low to moderate speeds. At high speeds their efficiency may fall to eighty-five percent or so. Even that is very good.

Twentieth-century cars and trucks relied on waste heat from the engine to keep their passengers warm. The traditional automotive heater contained a small radiator warmed by hot water from the engine's cooling system.

An electric motor does not produce enough heat for this type of heater. A battery vehicle's heater draws energy from the battery, energy that would otherwise be used to drive the vehicle.

Regenerative Braking

As well as converting almost all of their fuel into work, battery vehicles recycle energy. They can do this because they have regenerative braking systems.

An ordinary braking system slows a vehicle by converting the energy of its forward motion into heat, which is why brake discs and pads get warm. The harder the driver uses the brakes, the hotter they get. TV coverage of the Bathurst 1000 often shows dramatic images of pit crews in heat resistant gloves, using tongs to change smoking brake pads. All that heat comes from the energy of the car's forward movement: Its Kinetic Energy. The amount of energy depends on the vehicle's speed and weight: The faster it goes, the greater its kinetic energy. Kinetic energy comes from the fuel consumed by the engine as it accelerates the car. A conventional car cannot recapture this energy. The only way to slow it down, aside from crashing it into something, is to convert its kinetic energy into heat. It's very difficult to re-use heat from a conventional braking system.

A regenerative braking system can recycle energy because the operating principle of an electric generator is a mirror image of the principle behind the electric motor. When electricity flows through a loop of wire in a magnetic field, the loop wants to move: If you move the loop you force electricity through the wire. Electric vehicle designers exploit this by connecting the vehicle's brake pedal to the motor's control system. Every time the driver touches the brakes, every time they coast down a hill, every time they take their foot off the juice, the motor transforms itself into a generator and pumps electricity into the battery. It takes work to charge a battery. The faster the motor scoops electricity into the battery, the harder it slows the vehicle. Instead of wasting energy by warming up brake pads, a regenerative braking system scrapes up kinetic energy and returns it to the battery, boosting the vehicle's operating range and dramatically reducing wear and tear on its conventional brake pads. Modern electronic control systems are so good that one battery car manufacturer reckons they can programme their regenerative braking system to stop their car without using its mechanical brakes at all.

Recharging

Recharging has traditionally been the major weakness of battery vehicles. The Tesla Roadster is horrible: it takes at least three and a half hours to recharge its lithium-ion battery from flat.

IF you happen to have access to an industrial-grade wall socket.

If you're forced to use an ordinary domestic socket, it takes at least 26 hours.

Battery vehicle manufacturers are trying harder. Tesla Motors recently unveiled the design of their Model S, a family hatchback that recharges in 45 minutes, and, if you buy the optional extra big battery pack, a range of 480 kilometres. The real thing will not be available till 2011, but if it lives up to the spin it might just be practical. It could drive from Auckland to Wellington in a single day, just like a '74 Valiant: If you don't mind stopping halfway and dawdling over a very long lunch, and if you can find a filling station with a suitably humongous power outlet.

Some electric vehicle manufacturers hint at even faster recharging. For example, Italy's Micro-Vett recently demonstrated a tiny electric panel van fitted with a new type of lithium-ion battery, somewhat heavier than a conventional lithium-ion battery of comparable capacity. It can be recharged in ten minutes. Who knows if ten-minute recharging will become the norm? The battery might be astronomically expensive, or it may have some other fatal flaw. However, Tesla's 45-minute recharge time is feasible with conventional lithium-ion batteries and sensible engineering. What they have not revealed, yet, is the total weight of the Model S when fitted with the long-range battery pack. It might be rather hefty.

Range and Payload

It's one thing to build a battery car, but what really matters is whether battery technology can deal with all practical transport operations. New Zealand farmers depend on full-sized trucks to get their produce to freight depots. If you drive around rural highways on a workday, you'll see plenty of 44-tonners, similar to the trucks that stock up our supermarkets.

A 44-tonne truck typically burns about 350 litres of diesel to get from Auckland to Wellington. A battery-powered truck needs 1096 kilowatt-hours of battery capacity to do the same amount of work as 350 litres of diesel[18]. Let's suppose our trucker is happy to recharge their battery half-way through each workday: That's 548 kilowatt-hours per charge.

Battery capacity gradually fades, as if battery vehicles are cursed with perpetually shrinking fuel tanks. Conventional lithium-ion batteries have a calendar life of about five to seven years, that is, they gradually lose their ability to store energy, whether they are used or not.

According to Tesla Motors: *The battery pack in your Tesla Roadster is expected to maintain good driving performance for about 100,000 miles or five years, whichever comes first. Lithium-ion batteries will degrade slightly over time. Our testing and modeling indicate that a typical Tesla Roadster owner who drives 50,000 miles [80,450 km] over five years should have about 70 percent of initial performance levels available*[19]. In other words a five-year-old Tesla Roadster with 80,450 kilometres on the clock will have about seventy percent of its original operating range.

A trucker would want to hold some capacity in reserve, so they don't run out before they reach the charging station, somewhere near Turangi. The battery should be large enough to allow for some loss of capacity with age, say thirty percent. Allowing for a fifteen percent reserve, our electrochemical truck needs a battery capable of holding 900 kilowatt-hours when it is new. This battery would weigh about 7.6 tonnes[20].

Even this gigantic battery won't satisfy a southern trucker. Battery capacity shrivels in cold weather, so a cold battery holds less charge than a warm one. Frigid conditions make batteries sluggish, so the truck will tend to be gutless on a Southland winter morning. Practical electric vehicle batteries have thermal management systems that warm them up in cold weather. These use energy from the battery. Not only that, but the battery must also supply enough energy to heat up the inside of the cab. Taking all these issues into account, you can bet that southern truckers will need bigger batteries than truckers who never go south of Auckland. Long-distance types that drive from one end of the country to the other will also need big, hefty, Southland batteries.

We can get a rough idea how this might affect transport in New Zealand by comparing the maximum payload of a battery truck, with that of a conventional diesel truck. The battery won't reduce the truck's payload volume. However, it dramatically reduces the payload weight.

A typical 44-tonne semi-trailer (articulated truck), has an unladen (tare) weight of about nineteen tonnes and a payload of twenty-five tonnes. A battery-powered semi-trailer would have a tare weight of 25.2 tonnes, and a payload of 18.8 tonnes. It would carry only seventy-five percent of the freight carried by a diesel truck. Southern truckers would carry even less, because their extra-large batteries slash payloads.

Battery-powered trucks would dramatically reduce the efficiency of transport in New Zealand. It would take at least four battery-powered trucks to do the work of three full-size diesel trucks, provided battery-powered truckers can add a refuelling stop into what is already a very busy workday. If each milk tanker carries a quarter less milk, traffic needs to increase by a third to carry the same amount of milk. Some roads would need upgrading to carry the extra traffic. Freight depots would need expanding. We'd need a lot more truck-drivers with the right skills to drive 44-tonne trucks on New Zealand's narrow twisting roads. The cost of labour, of replacing trucks as they wear out, of tyres, and of road user charges, would all increase by a third, so unless the running costs of battery trucks are a great deal lower than those of diesel trucks, New Zealanders would all face substantial increases in real freight costs.

Medium-sized battery trucks on low-speed urban routes look more practical. For example, British manufacturer Smith Electric Vehicles is flat-out building small and medium-sized vans and trucks for the UK market, where some cities offer heavy subsidies for low-emission vehicles. Smiths' biggest product is the Newton, which has a maximum loaded weight of 12 tonnes. The chassis weighs 4,900 kilograms with batteries and a standard cab, leaving 7,148 kilograms for the truck body and payload[21]. An empty Smith Newton weighs about two tonnes more than a diesel truck of similar capacity, so its fully loaded weight is greater than a comparable diesel truck. This is not a major problem, because it is too slow to damage urban roads.

Smith Electric Vehicles say the Newton has a range of *up to 150 miles* (240 km). After allowing for battery ageing and reserve capacity, this leaves a practical range of about 173 kilometres. A full recharge takes about eight hours, which means it can't be recharged in the middle of the workday. It's only practical for carriers who average less than about 22 kph across an eight-hour day. That's OK in seriously constipated cities such as London, where the traffic struggles to average 20 kph, but it would be totally useless for small-town or rural New Zealand truckers.

Cost

Battery vehicles should be cheap to make, if we could ignore the battery. Manufacturing costs depend on three basic factors: the cost of materials, the complexity of the manufacturing process, and the production volume. Traction motors weigh a great deal less than comparable petrol or diesel engines, which means they contain less material. The materials are not particularly exotic, which means they are not exorbitantly expensive. An electric motor has only one moving part, the rotor, whereas a petrol or diesel engine has dozens of bearings and con-rods and pistons and other moving parts. Battery vehicles don't need complex gearboxes: Tesla's electronic handbag hauler only has one gear. The electronic control system uses the type of technology found in computer power supplies, so it can be expected to be extremely cheap.

Maintenance costs should also be very low. Apart from the battery, there is almost nothing to wear out. Battery vehicles require next to no maintenance and they should last a very long time.

Battery vehicle manufacturers rave about the low cost of recharging batteries. They're not wrong. Based on road tests that compared battery cars with similar petrol models, I reckon a battery-powered motorist needs to purchase 2.45 kilowatt-hours of electricity to get enough juice to do the work of a litre of petrol. It takes more electricity to do the work of a litre of diesel, because diesel engines use fuel more efficiently than petrol engines: A diesel trucker must buy 3.36 kilowatt-hours to get the equivalent of a litre of diesel[22].

Small battery cars can be recharged from domestic power sockets. This would cost the equivalent of 54 cents per litre of petrol at the average domestic price of electricity in 2007: 22 cents per kilowatt-hour. Truckers would pay even less, because they would use so much power they'd probably get the commercial price: 14 cents per kilowatt-hour (excluding GST). At that price a battery-powered trucker would pay about 47 cents for the equivalent of a litre of diesel (excluding GST)[23]. Even when we add road user charges, ACC levies and other tariffs, fees, and taxes, it still kicks the stuffing out of fossil fuel prices.

So. What's the catch?

The catch is that battery vehicles do not run on electricity. They run on batteries.

We all know that rechargeable batteries are consumable items. Cellphone batteries wear out within a few years, and of course cellphone shops never seem to have replacements, which is why some greenies dedicate their spare time to campaigning against electronic rubbish. Batteries are made out of individual cells, and most present-day battery vehicles use lithium-ion cells: For example, the Tesla Roadster's 450-kilogram battery has 6,831 individual cells, of a type similar to those in cellphone batteries. Just like a cellphone battery, it won't last forever. Some other vehicle batteries use newly-developed variations on the lithium-ion theme. Others use older types. Whatever the underlying technology, history shows that batteries wear out; usually far quicker than the equipment in which they are used. The cost of replacing batteries far outweighs the cost of electricity. We have to dramatically stretch reality to call battery-powered cars and trucks: "electric vehicles". Electric trains and trams are electric vehicles. They don't have batteries.

The running cost of a battery vehicle must take account of two separate items: The cost of recharging the battery; And the cost of the battery itself. Batteries wear out, or go rotten, so the cost of replacing the battery must be divided by its working life (*Depreciation*). If we know the working life, we can compare the battery and recharging costs with the cost of buying enough petrol or diesel to do the same amount of work.

Predicting the life expectancy of rechargeable batteries is surprisingly complex. If they are completely flattened and fully recharged during every charge/discharge cycle, conventional lithium-ion batteries tend to last between 500 and 1,000 cycles. They also have a limited calendar life: their capacity gradually fades and their performance falls off over time. This is caused by chemical changes inside the battery. Like fruit in a bowl, batteries gradually rot, whether we use them or not.

It's tempting to think a conventional lithium-ion battery would last about 500-1,000 full charge/discharge cycles or about seven years, whichever comes first. The trouble is that batteries are far more complex than that. Imagine a trucker who drives a regular run, day-in, day-out. They'll need a battery that will do the entire run, even at the end of its life, with enough reserve capacity to cover contingencies. The first time they use a brand-new battery, they will not fully discharge it. It will lose some capacity, but nowhere near as much as if they fully discharge it. Each day, the trucker will take that battery just a little closer to full discharge, not because they drive further, but because the battery capacity has shrunk. Back in the '80s I worked on a project involving battery-powered equipment. The engineer who did the battery-life modelling spent days poring over piles of detailed information about the batteries, or slaving over his PC tinkering with his mathematical model, which at best gave only a very rough idea of how long our rechargeable batteries would last. I'm not sure if I have the patience for that kind of work. The point is that the only practical way to find out how long truck batteries will last is to wait until truckers have been using them for some decades, and then do a detailed mathematical analysis of the life history of their batteries. That will yield the necessary information for a statistical model of the battery life in real-world conditions. Once that is done, it would then be possible to say that in a given set of conditions, such and such a model of battery would have a certain probability of surviving such and such a period of time.

This kind of engineering model would be quite useful for practical transport operators if they were still interested in the types of batteries used in the original study. The trouble is that manufacturers keep inventing new kinds of batteries with totally different operating characteristics, so, of course, the mathematical model would be useless before it was ever built.

However, there's enough publicly-available information to estimate the approximate cost of battery wear and tear.

David L. Anderson at Duke University in North Carolina recently developed a mathematical model for predicting the cost of lithium-ion batteries. According to the scenarios in his model, battery prices in 2030 might be somewhere between $US 200 per kilowatt-hour and about $US 730 per kilowatt-hour of capacity[24].

Researchers at Argonne National Laboratory estimated in 2009 that batteries for plug-in hybrid vehicles with an all-electric range of 60 km might eventually come down to about $US 300 per kilowatt-hour of capacity[25].

Another way of checking the battery cost is to look at a manufacturer's price list. According to marketing bumph from Tesla Motors, a US-based roadster owner would currently pay $US 12,000 ($NZ 17,640) to replace their battery: $US 224 per kilowatt-hour of capacity[26]. However, we have no idea if Tesla can make a profit on batteries at that price.

We can use these projections to estimate how battery wear and tear would affect the cost of running a family car. Based on the most optimistic projections, the cost of a battery divided by its operating life, is equivalent to $NZ 3.674 per litre of petrol in a conventional car[27]. Add the cost of electricity to charge the battery, and the total fuel and battery cost adds up to the equivalent of $4.21 per litre of petrol, plus taxes. These costs do not include the cost of freighting the battery to New Zealand.

The running costs of battery vehicles are extremely sensitive to battery life expectancy. The Tesla's battery is looking decidedly sick after 5 years or 80,450 kilometres. If they could treble that, which is what battery developers are hoping to do, then the total fuel and depreciation cost falls to the equivalent of $1.22 per litre of petrol, excluding taxes and freight.

The cost of running commercial battery vehicles is less sensitive to calendar life. A trucker or courier who uses two charge-discharge cycles per day can get through 480 cycles per year. If the battery survives 1500 cycles it would last a little more than three years. Calendar life wouldn't matter, because the battery would wear out long before it goes rotten. Assuming prices fall to $US 224 per kilowatt-hour of capacity, a trucker who uses up a 900 kilowatt-hour battery in three years would spend, on battery depreciation and electricity, the equivalent of $NZ 1.68 per litre of diesel (excluding GST, road user charges, freight on the battery, and so on)[28]. This assumes battery prices fall to $US 224 per kilowatt-hour of capacity.

At present, they cost about $US 1,000 per kilowatt-hour of capacity. At that price, a battery-powered motorist would spend the equivalent of about $NZ 16.92 per litre of petrol, and a battery trucker would cough up the equivalent of $NZ 5.73 per litre of diesel.

Some vehicle manufacturers don't sell batteries. They lease them. This bundles all the costs into a regular monthly charge, but it doesn't make the costs go away. The leasing company must recover the cost of the battery, and make a profit, across the battery's working life, unless it wants to go broke. So, instead of forking out tens of thousands of dollars on batteries, motorists and transport operators would make monthly payments, the total of which would cover the cost of the battery and the leasing company's profit margin.

Applications for Battery Vehicles

Battery vehicles will be restricted to road transport for a very long time. It seems unlikely that battery technology will make any significant inroads into mainstream aviation, and equally unlikely that it will displace fuel oil from the shipping industry. For the amount of energy they can store, batteries are way too heavy. A kilogram of jet fuel, diesel, or fuel oil contains about 12.5 kilowatt-hours of energy. A kilogram of lithium-ion battery can hold about 1.2 kilowatt-hours. Battery enthusiasts insist that electric motors can get more than twice as much work from a kilowatt-hour of electricity stored in a battery, than a diesel or gas turbine engine can get from a kilowatt-hour of energy stored in its fuel. That seldom compensates for the very low Specific Energy of batteries. (Specific energy is measured in kilowatt-hours per kilogram or tonne.) Battery-powered aircraft are doing extremely well to lift the weight of their batteries off the ground. Don't expect them to compete with jet airliners anytime soon.

Battery-powered tractors would be equally unsatisfactory. For example, the 80 kilowatt John Deere 7130 comes standard with a 208 litre diesel tank, which is enough for slightly less than ten hours work at three-quarters of maximum load. A battery capable of holding enough energy to do that much work would weigh more than nine tonnes, which is shiploads more than the JD7130's all-up weight of just over five tonnes. Battery-powered tractors would be impractical. The battery would need to be carted back and forth between tractor and recharging station, a task that is way beyond the capability of an ordinary ute or pickup truck. You'd need a heavy-duty truck with a hydraulic hoist.

Rural power grids would struggle to recharge such stupendous batteries in a reasonable time. A battery-powered agricultural contractor would have to take their batteries to town, to find enough power to charge them. That would put a lot more heavy traffic on rural roads.

Battery-powered boats are finding a niche in the vast canal systems criss-crossing Europe and the UK. Canal cruisers travel very slowly, and they use very little energy. They can plug in to recharging stations whenever they tie up for the night. However, New Zealand has no canals, and most of our boats are used in the open sea. They need liquid fuels.

Vehicle and battery manufacturers are pouring vast sums of money into battery development. As we'll see in Chapter 7, there are some indications they might succeed. In the next couple of chapters, we'll look at the kind of infrastructure New Zealand would need to support large-scale deployment of battery-powered road vehicles.