Low-emission fuel-efficient light vehicles

November 2009

J de Pont
TERNZ Ltd
Auckland

NZ Transport Agency research report 391

ISBN 978-0-478-35245-0 (print)
ISBN 978-0-478-35244-3 (electronic)
ISSN 1173 3756 (print)
ISSN 1173-3764 (electronic)

NZ Transport Agency
Private Bag 6995, Wellington 6141, New Zealand
Telephone 64 4 894 5400; facsimile 64 4 894 6100
research@nzta.govt.nz
www.nzta.govt.nz

de Pont, JJ (2009) Low-emission fuel-efficient light vehicles. *NZ Transport Agency research report 391.* 118pp.

Keywords: alternative fuels, emissions, fuel efficiency, GHG, greenhouse gas, light vehicles

An important note for the reader

The NZ Transport Agency is a Crown entity established under the Land Transport Management Act 2003. The objective of the Agency is to undertake its functions in a way that contributes to an affordable, integrated, safe, responsive and sustainable land transport system. Each year, the NZ Transport Agency funds innovative and relevant research that contributes to this objective.

The views expressed in research reports are the outcomes of the independent research, and should not be regarded as being the opinion or responsibility of the NZ Transport Agency. The material contained in the reports should not be construed in any way as policy adopted by the NZ Transport Agency or indeed any agency of the NZ Government. The reports may, however, be used by NZ Government agencies as a reference in the development of policy.

While research reports are believed to be correct at the time of their preparation, the NZ Transport Agency and agents involved in their preparation and publication do not accept any liability for use of the research. People using the research, whether directly or indirectly, should apply and rely on their own skill and judgement. They should not rely on the contents of the research reports in isolation from other sources of advice and information. If necessary, they should seek appropriate legal or other expert advice.

Acknowledgements

In undertaking this research, the author was supported by a steering group who reviewed progress and provided guidance on directions and issues to pursue.

The final report was peer reviewed before submission.

I would like to thank both the steering group and the peer reviewers for their guidance and assistance.

Contents

Executive summary

To assist in meeting climate change commitments, there is a target to reduce the per-capita greenhouse gas (GHG) emissions from transport to half the 2007 levels by 2040. Light vehicles currently account for 93% of the total kilometres travelled by the vehicle fleet in New Zealand, and about 81% of the GHG emissions. Thus, reducing the emissions of the light-vehicle fleet is crucial to achieving this target, and this research aimed to identify opportunities for doing so.

GHG emissions are primarily carbon dioxide (CO_2), with small contributions from other gases. Consequently, CO_2 emissions can be used as a surrogate measure for GHG emissions. As CO_2 emissions are directly related to fuel consumption, improving fuel efficiency reduces GHG emissions.

Vehicles generate other emissions that are not directly considered GHGs. These emissions affect air quality and are claimed to cause around 500 premature deaths per year in New Zealand. The various emissions standards imposed in different jurisdictions primarily target these air-quality emissions and do not address the GHG emissions. In this study, we considered both types of emissions, as it is important to consider the total effect of changing the emissions profile of the nation's vehicle fleet. Reducing GHG emissions at the expense of air-quality emissions, or vice versa, is not desirable.

A range of low-emission light vehicles is in use today, and it is likely that future vehicles, in the short to medium term, will be based on developments of these vehicles. These developments could include improved efficiency, new engine and fuel technologies, weight reductions and improved aerodynamics, energy recovery, and so on. Current vehicles can be separated into the following broad categories:

- human-powered and hybrid human-powered vehicles
- low-powered urban vehicles with restrictions on speed and power
- unrestricted vehicles.

This study begins with a review of the range of vehicles currently available in each of these categories and the rules and regulations applying to them. In general, the rules and regulations applying to vehicles have evolved in response to the specifics of known vehicle types, rather than for generic categories. This means that for common vehicles, such as cars and bicycles, the rules are typically quite well defined and clear, while for more unusual and new vehicle configurations, such as skateboards and the Segway personal mobility device, there is often a degree of ambiguity and, in many cases, a lack of any rules. We believe there is a need for a consistent set of principles that defines vehicle categories and the rules governing their use.

We reviewed a number of the fuel and vehicle technologies that are currently available or are under development. Comparing fuel efficiency is complicated because of variations in the energy density of the different fuels. To simplify this, we used GHG emissions, which are measured in g/km of CO_2-e (equivalent), as the basis for comparison. GHG emissions reflect the combined effect of energy content and the efficiency of the engine in using that fuel. Our key findings are as follows:

- Diesel, LPG and CNG are all well-established fuels and can reduce GHG emissions at the tailpipe by about 20–30%, compared to petrol.
- Biofuels generate similar levels of GHG emissions at the tailpipe to the fuels they replace, but because the production of the feedstock used for making them removes CO_2 from the atmosphere, there is the potential for a net reduction in GHG emissions when the whole fuel cycle is considered. For 1st-generation biofuels, this net reduction ranges from -30% to 174% – that is, in the worst cases there is

a net increase in emissions, while in the best cases there is a substantial gain. For 2nd-generation biofuels the GHG emission reductions are expected to be around 80–90%. Using low-level biofuel blends has only a small impact on overall GHG emissions, although it is a useful approach for getting the fuel technology established so that higher-level blends can be used in the future.

- Synthetic fuels, such as DME and Fischer-Tropsch diesel, also produce similar tailpipe GHG emissions to the fuel they replace. However, in general, the production process for these fuels also generates GHG emissions, so the overall effect is an increase in GHG emissions.
- Hydrogen is essentially a carrier of energy, rather than a fuel in its own right. Some other form of fuel (electricity or natural gas) is used to generate the hydrogen, which is subsequently converted back to energy for transport. Because of its low density, hydrogen needs to be either liquefied or compressed to very high pressures in order to be transported efficiently. The losses and emissions associated with the energy conversions and the transport and handling of the hydrogen means that with current technology, it is better to use the fuel in its original form rather than convert it to hydrogen.
- Mild hybrids, which use an up-rated starter motor and alternator to provide stop/start capability and regenerative braking (but do not have electric drive capability), can reduce GHG emissions by around 10% depending on the amount of congested urban driving.
- Fully grid-independent hybrids can reduce tailpipe GHG emissions by more than 40%. However, there are increased emissions associated with the manufacturing and disposal of the vehicle. On a life cycle basis, the reduction in GHG emissions is about 25%.
- Battery electric vehicles produce the lowest GHG emissions. This is particularly so in New Zealand, where the average mix of electricity generation includes about 70% from renewable sources. On a whole-life-cycle basis, using average power, battery electric vehicles produce about 40–45% of the GHG emissions of a petrol equivalent. At the tailpipe, they produce zero emissions.
- Plug-in hybrids will have GHG emissions somewhere between those of grid-independent hybrids and battery electric vehicles, depending on use.
- Batteries are still a major constraint on electric vehicles in terms of weight, cost, energy density and recharge times. Hydrogen-based fuel cells provide an alternative to batteries, but as noted above, this is less efficient. Other alternatives, such as ultracapacitors, are also being developed but as yet have not overcome the limitations of batteries.

Vehicle registration data indicates that approximately 85% of New Zealand's light-vehicle fleet is petrol-powered and 15% is diesel-powered. Eighty-seven percent of these vehicles are light passenger vehicles, and these undertake 85% of the distance travelled. The remainder are light commercial vehicles. The Ministry of Transport's annual household travel survey shows that 76% of household trips, representing 94% of distance travelled, are undertaken by car or van. Clearly the biggest potential gains in fleet fuel efficiency and GHG emissions performance can be achieved from petrol-powered light passenger vehicles.

There are three ways in which the fuel efficiency and GHG emissions performance of the light-vehicle fleet can be improved:

1. Downsizing – using smaller-engined, lighter cars:
   There is considerable evidence to show that many people are using cars that have larger engines and weigh more than is necessary to meet their functional requirements. If all passenger-car drivers (except those currently driving vehicles in the smallest engine-size category) changed to a vehicle that was one engine-size category lower than their current vehicle, the reduction in GHG emissions and fuel consumption would be approximately 14%. In most cases, this change could be achieved without

a significant loss of vehicle carrying capacity. If the change was to two engine-size categories down, the potential reduction in GHG emissions would be 22%. Light commercial vehicles are generally selected on a more strictly economic basis to match the requirements of the task, and thus have little scope for downsizing.

2 Changing fuel/engine technology to a more fuel-efficient, lower-emissions alternative:
As noted above, the currently available alternative fuels (diesel and LPG) provide GHG reductions of about 20%; petrol–electric hybrids generate GHG reductions of around 25%; mild hybrids can produce GHG reductions of about 10% without the complexity of a full hybrid; and battery electric vehicles can reduce GHG emissions by 55–60% (or more) if only renewable electricity is used. However, in the short term, the price and availability of these vehicles will limit their market penetration. The use of biofuels as low-level blends with conventional fuels (E10 and B5) can result in small gains, depending on how and where they are produced (in the worst cases it can be negative). In the future, with 2nd-generation biofuels, and using high-level blends or pure biofuels, very substantial GHG reductions (80% or more) will be possible. Furthermore, New Zealand is well suited to developing an efficient domestic biofuel production capability.

3 Changing vehicle type to a more fuel-efficient category:
This is a bigger step for most drivers than downsizing, or changing fuel or engine technology. Although the potential reduction in GHG emissions is relatively large, it is usually associated with a significant change in functional capability. For example, changing from a small car to a moped reduces GHG emissions by about 80%, which is roughly comparable with changing from a large car (3000cc–4000cc) to a small car (<1350cc). In changing from a large car to a small car, the driver sacrifices some performance and some space, but retains the ability to carry passengers and luggage, and still has weather protection and full access to the entire road network. All of these functions are compromised when changing to a moped.

In order to support the development of policies that would encourage the use of lower-emitting, more fuel-efficient vehicles, we reviewed the following seven main factors that influence vehicle selection:

- size, capacity and vehicle type
- performance
- economics
- safety
- fuel efficiency and environmental impacts
- status and image
- government policy.

For most light commercial vehicles, economics is the primary factor – thus, the size and type of vehicle, the engine performance, and fuel efficiency will be optimised for the particular transport task. Safety will be controlled by the vehicle meeting regulatory requirements while, in most cases, status and image will not be a factor. Government policy can be a factor if it indicates future directions that could have economic advantages.

For light passenger vehicles, the picture is more complicated. Clearly, many people buy vehicles that are larger than they need, have capabilities that they never use, have performance far in excess of what can be used legally on New Zealand roads and are not the most economic choice for their needs.

Safety is an important consideration in vehicle choice and, in general, larger vehicles are safer for their occupants. However, this safety is achieved at the expense of being less safe for other road users. Overall safety is enhanced if cars are more similar in size. Also, although on average, larger cars are safer, there are a number of small cars among those with the best crashworthiness rating in the New Zealand and Australian vehicle fleet, and there are a number of large cars and large SUVs among those with the worst rating. Unfortunately, there are currently no very small cars among those with the best crashworthiness.

It has been found that while many car buyers state that fuel efficiency is an important consideration in their car-purchasing decision, their actual decision does not reflect this. With the recent volatility in fuel prices, there does appear to have been some change in this behaviour.

A number of intangible factors influence a person's choice of vehicle and these can effectively override considerations of fuel efficiency and economics. We have simplistically called these factors 'status and image'. Some people will pay a significant premium price for these factors. Thus if the 'status and image' associated with fuel-efficient, low-emission vehicle options can be made appealing to this market segment they will buy them, even if it is not best economic decision.

In the early 1980s, government leadership influenced the uptake of fuel-efficient, low-emission vehicles, with support for LPG and CNG vehicles. The economics of some of the alternative fuel options (such as biofuels) depend heavily on the world price of oil, which has been very volatile over the last two years. With the government's commitment to the use of biofuels, there was a guaranteed market for them in New Zealand, and at least two major international biofuel producers made plans to build plants in New Zealand. The government has now withdrawn the sales obligation for biofuels and these biofuel producers have cancelled their plans.

Based on our findings, we make the following recommendations:

- Some older vehicle technologies that are fuel efficient and produce low GHG emissions also produce relatively high air-quality or 'regulated' emissions. Encouraging technologies that meet the latest regulated emission standards would help the government meet the objective of reduced emissions.
- Compared to the fuel excise duty on petrol vehicles, the current road user charges (RUC) schedule effectively discourages small, fuel-efficient diesel cars and encourages large, less fuel-efficient diesel cars and SUVs. This could be rectified by replacing RUCs with a fuel excise duty for light diesel vehicles. This would require a modification of the RUC schedule for heavy vehicles.
- Standard-sized electric vehicles are just beginning to enter the market. At current pricing, the economics of battery electric vehicles is poor. Over time, it is expected that the price will decrease and the economics of these vehicles will improve. In the short term, information on electric vehicles could be included on government consumer information websites to encourage interest.
- Smaller low-powered electric vehicles exist in significant numbers in other countries. At present, there is no provision for these vehicles to be used on New Zealand roads. We recommend a review of the potential role of these vehicles for lower-speed urban transport in New Zealand. The review would need to consider safety requirements, speed limits, road access restrictions and driver licence requirements.
- Downsizing can have a significant positive effect on fuel efficiency and GHG emissions without significant negative impacts on mobility. The government could investigate measures to encourage people to buy lighter cars with smaller engines, while still maintaining safety – with a particular focus on the current users of the larger vehicle categories. One approach could be to use the websites www.rightcar.govt.nz and www.fuelsaver.govt.nz to promote a positive image for using safe, more

fuel-efficient, smaller-engined vehicles. Reducing the range of vehicle sizes in the fleet would improve safety, and improved fuel efficiency would benefit the economy.

- In the longer term, biofuels will be able to produce substantial reductions in GHG emissions, using largely existing engine technologies with relatively minor modifications. New Zealand is well placed to become a significant biofuels producer and could, in the long term, become self-sufficient in transport fuel. This is something for the transport sector to pursue further.

Abstract

To assist in meeting climate change commitments, there is a target to reduce the per-capita greenhouse gas emissions from transport to half the 2007 levels by 2040. Light vehicles contribute 93% of the total kilometres travelled by the fleet in New Zealand, and about 81% of the greenhouse gas emissions.

This report reviews the range of light vehicles available today. It considers the fuel and engine technologies that are available at present or will be become available in the near future. For each of these vehicle, fuel and engine technologies, the emissions and fuel efficiency performance is evaluated.

The transport demand for light vehicles is assessed, and a range of options for improving the fuel efficiency and emissions performance of the New Zealand light-vehicle fleet are considered.

1 Introduction

To assist in meeting climate change commitments, there is a target to reduce the per-capita greenhouse gas (GHG) emissions from transport to half the 2007 levels by 2040 (Ministry of Transport 2008a).

Light vehicles currently account for 93% of the total kilometres travelled by the vehicle fleet in New Zealand, and about 81% of the transport-generated greenhouse gas (GHG) emissions. Thus, reducing the emissions of the light-vehicle fleet is crucial to achieving this target, and this research aimed to identify opportunities for doing so.

We reviewed the fuel and engine technologies currently available (or will become available in the near future), the range of light vehicles available today, and their emissions and fuel efficiency performance. The transport demand for light vehicles was assessed, and a range of options for improving the fuel efficiency and emissions performance of the New Zealand light-vehicle fleet was considered.

GHG emissions are primarily carbon dioxide (CO_2), with small contributions from other gases. Energy Information and Modelling Group 2008 data shows that the total GHG emissions from regular petrol are 2.32kg/l of CO_2-equivalent (CO_2-e), but the contribution from actual CO_2 is 2.29kg/l. Thus the contribution of other gases is only just over 1%. For diesel, the figure is just under 2%. Consequently, CO_2 emissions can be used as a surrogate measure for GHG emissions. As CO_2 emissions are directly related to fuel consumption, improving fuel efficiency reduces GHG emissions. Improving fuel efficiency also has significant economic benefits through reducing costs and increasing productivity.

Vehicles generate other emissions that are not directly considered greenhouse gases. These include NO_x (oxides of nitrogen), particulate matter (primarily from diesel engines), carbon monoxide, and non-methane volatile organic compounds (NMVOCs). These emissions affect air quality and are claimed to cause around 500 premature deaths per year in New Zealand (Fisher et al 2007). The various emissions standards imposed in different jurisdictions, such as the Euro and environmental protection agency (EPA) requirements, primarily target these air-quality emissions and do not address the GHG emissions. In New Zealand, the Vehicle Exhaust Emissions Rule 2007 specifies the requirements for both new and used imported vehicles. These are based on complying with one or other of the international standards. The stricter emission standards that are scheduled to come into force over the next few years should have a significant impact on air quality, but will have little direct effect on GHG emissions.

In this study we considered both types of emissions, as it is important to consider the total effect of changing the emissions profile of the nation’s vehicle fleet. Reducing GHG emissions at the expense of air-quality emissions, or vice versa, is not desirable.

A range of low-emission vehicles is in use today and it is likely that future vehicles, in the short to medium term, will be based on developments of these. These developments could include improved efficiency, new engine and fuel technologies, weight reductions and improved aerodynamics, energy recovery and so on. Current vehicles can be separated into the following broad categories:

- human-powered and hybrid human-powered vehicles
- low-powered urban vehicles with restrictions on speed, power and possibly weight
- unrestricted vehicles.

Each of these categories can be further sub-divided.

This report begins, in sections 2, 3 and 4, by considering the current status of vehicles in each of these categories internationally. This includes the fuel efficiency, emissions levels, and the regulatory and policy framework under which they operate.

In section 5, we review the fuel and engine technologies that are currently available, or under development and likely to become available in the near future.

Section 6 presents an analysis of the current light-vehicle fleet in New Zealand and the travel patterns of New Zealanders using this fleet.

In section 7, the findings from sections 5 and 6 are combined to determine the potential reductions in GHG emissions that could be achieved from specific changes to the New Zealand light-vehicle fleet and the way it is used. Various methodologies for comparing emissions performance are reviewed and applied.

In order to achieve change to the New Zealand vehicle fleet, we need to have some understanding of the factors that influence vehicle selection. These factors are discussed in section 8.

Section 9 concludes the report by summarising the key findings and making recommendations for policy initiatives to improve the fuel efficiency and emissions performance of the light-vehicle fleet.

2 Human-powered and hybrid human-powered vehicles

2.1 Bicycles

The most widely used vehicle in this category is the bicycle, which was invented about 40–50 years before the automobile. For the latter half of the 19th century and the first half of the 20th century, it was the dominant form of personal transport. In some countries it has retained this role for much longer. The bicycle is well established in legislation as a legitimate vehicle and there are a number of regulations specifying the requirements for bicycles and cycling.

As a vehicle for personal transportation, the bicycle is extraordinarily energy efficient. Whitt and Wilson (1982) presented a detailed discussion, with extensive references, of the power and energy requirements of cycling. The energy requirements depend on a number of factors, including speed, gradient, rider weight and the type of bicycle. At 24km/h on a 'roadster' bicycle, the energy use was given as 24.4kcal/km, which equates to about 360km/l of petrol. They found that a racing cyclist at the same speed used energy at less than half this rate, and for the same energy use, could travel at about 38km/h. By comparison, they found that a moped and rider at 32km/h achieves approximately 100km/l; a car with five occupants at 50km/h achieves about 72km/l per occupant; and a car with one occupant at 50km/h achieves 16km/l.

Templeton (2008) argued that the bicycle energy consumption figure should be multiplied by 10 for the US because the energy involved comes from food, and American agribusiness uses 10 units of fossil fuel energy to produce one unit of food energy. While this argument has some major flaws, it does raise an important issue. All forms of energy are not equal, and we should consider the energy involved in producing and distributing the fuel. A counter-argument is that for most cycle trips, the amount of exercise involved is less than the minimum desirable level required for healthy living, and there is no need for additional food energy intake by the rider.

The bicycle also has an extraordinary load-carrying capacity for its weight. It is not unusual to see a 90kg plus rider on a bicycle weighing less than 10kg. Thus, more than 90% of the total weight is payload. Considering cargo only, the Dutch 'bakfiets' shown in figure 2.1 weighs approximately 27kg and is designed to carry a payload of 125kg in addition to the rider. If the rider is not considered part of the load, then assuming a rider weight of 73kg, the payload is 56% of the total weight. Although most large heavy goods trucks can achieve a greater payload:total weight ratio than this (for example, in New Zealand a typical logging truck and trailer combination can legally operate at 44 tonnes gross combination weight, and at least 28 tonnes, or 64%, of this is payload), a typical utility vehicle, or 'ute', does not – here, the payload capacity is about 1 tonne out of a gross weight of 2.8 tonnes; that is, the cargo is 36% of the total weight. Thus, as a cargo vehicle the bicycle compares favourably with smaller vehicles, even when those vehicles are specifically designed for carrying cargo.

Increasing concerns about global warming, together with the issues of obesity and inactivity, have resulted in many jurisdictions developing policies to increase the use of active modes of transport (cycling and walking). The success of these policies has been extremely varied and it is worth reviewing the different approaches used, in order to identify the key factors affecting the success (or otherwise) of these policies. A recent study (Pucher and Buehler 2008) compared the cycling rates in the Netherlands, Germany and Denmark with those in the UK and the US. These figures ranged from 27% of all trips in the Netherlands, 18% in Denmark, 10% in Germany, down to about 1% in the UK, US and Australia. New Zealand was not listed in this study, but the results of the 2007 New Zealand Household Travel Survey, undertaken by the Ministry of Transport, quoted a figure of 1% (Ministry of Transport 2008b).

Figure 2.1 A Dutch 'bakfiets' (en.wikipedia.org)

There is a perception that the Netherlands is a special case and that the approaches used there are not applicable elsewhere. However, between the years 1950 and 1975, cycling levels in the Netherlands plummeted as they did in most other developed countries – between 1952 and 1975, cycling in the Netherlands dropped by 62%, and in the UK by 80%. In the mid-1970s, transport and land-use policies in the Netherlands, Denmark and Germany shifted dramatically to favour walking, cycling and public transport over the private car. Cycling in the Netherlands has rebounded and currently, cycling is at just over half its 1952 level, whereas in the UK, the decline has continued and currently it is at less than one seventh of its 1952 level.

2.2 Recreational devices

Bicycles are not the only human-powered vehicles in use for transport. We can identify two other broad categories:

- recreational devices, which include skateboards, kick-scooters[1], roller skates and in-line skates
- 'human-powered vehicles' (HPVs), which are typically derived from bicycle technology, but have different geometry and may have body shells.

Recreational devices are less fuel-efficient than bicycles, but there has been relatively little research on this. Whitt and Wilson (1982) compared the world records (for average speed for one hour) of cyclists and roller skaters. At that time, the best roller skater achieved 36km/h, while the best cyclist achieved 49km/h. Whitt and Wilson assumed that as both world record holders were top elite athletes, their power output would be similar and so the relative efficiency of the two vehicles could be estimated. Using the methodology outlined by Whitt and Wilson, we can calculate that at 24km/h, the roller skater needed to generate 305W of power. This is nearly double the power required by the 'roadster' cyclist. Thus, the

[1] The name 'scooter' is also used for a small-wheeled motorcycle with step-through geometry. To distinguish between the two vehicle types, we call human-powered scooters 'kick-scooters'.

energy consumption of a roller skater at this speed is 45kcal/km, which is equivalent to approximately 200km/l of petrol consumption. In practice, a recreational roller skater would travel more slowly and would use less energy per km.

The current speed records for 30km and 50km (as at September 2006) for in-line skaters on a track are at an average speed of approximately 37km/h. Thus the difference in efficiency between in-line skates and traditional skates is quite small. Skateboards are not raced, and so this method of analysis cannot be applied to them.

Kick-scooters have evolved from the child's toy type, with solid tyres and poor-quality bearings, through to aluminium folders with in-line skate wheels, and more recently, to larger models with bicycle wheels. These latest kick-scooters are raced. Although we have not found any world records, at the 2006 world championships the winning times for the marathon reflected an average speed of approximately 30km/h. This suggests that kick-scooters are slightly less efficient than skates.

These kick-scooters are comparable to bicycles in terms of their aerodynamic drag and rolling resistance, so the difference in speed is almost certainly due to the less-efficient drive mechanism. At 30km/h on flat ground, the power required by a racing bicycle is approximately 132W. At 48km/h the power required is 487W. The 100km team time trial at the Olympics is typically won in just over two hours, which is an average speed of more than 48km/h. When drafting, the power required is significantly less, and so it is not necessary for each rider to maintain an output of 487W to average this speed.

The same argument applies to scooter racing, where drafting also occurs, and so it is reasonable to assume that the scooter riders at the 2006 world championships were applying about 480W of power to deliver 130W to the scooter. That is, the scooter drive mechanism is only 27% efficient. Skateboards use a similar drive mechanism, and so approximately the same efficiency would be expected.

The regulatory environment for recreational devices in New Zealand is more complicated than for bicycles. Scooters, skateboards and skates are all defined as vehicles under the Land Transport Act (1998), but the Act does not specify where they can be used. The Land Transport (Road User) Rule (2004) introduces an explicit definition of a 'wheeled recreational device' and specifies a number of obligations for users of these devices. Wheeled recreational devices may be used on the footpath but they must be operated in a 'careful and considerate manner', at a speed that does not constitute a hazard to other footpath users, and they must give way to pedestrians and mobility vehicles. A further complication is that local by-laws may override this and prohibit the use of these vehicles on some footpaths. However, wheeled recreational devices may also be legally used on the road. Interestingly, although there are a number of legal requirements for bicycles, such as brakes, reflectors, helmet wearing, and lights when used at night, there are no similar requirements for recreational devices. Skates and skateboards typically do not have brakes but they can still be legally used on the road.

In the US and Canada, the regulations governing the use of recreational devices appear to be determined at the local government level. Many jurisdictions ban their use on roads and footpaths, although these regulations are widely disregarded. Other jurisdictions allow their use on footpaths, except in specified areas such as business districts, and in some cases on minor roads. The Economic Commission for Europe Working Party on Road Traffic Safety 2001 considered the safety of skaters and skateboarders and undertook a survey of member (European) countries to find out the regulations applying in those countries. They obtained 23 responses, and their findings were as follows:

- Most countries do not have special provisions in their national legislation that address this group of road users. A few countries stated that they do have legislation applying to this group, and a few countries have legislation that specifically defines this group as pedestrians.

- Most countries stated that people in this group were regarded as pedestrians.

The following recommendations for skateboarders, roller skaters, in-line skaters and so on have been drawn from the responses:

- They should be treated as pedestrians and should respect the traffic rules applicable to pedestrians.
- They should use the pavement (sidewalk) and should not disturb the movement of ordinary pedestrians.
- If there is no pavement, they may use an appropriate verge or part of the road reserved for pedestrians. When using the verge or the carriageway, they should keep to the side opposite to the direction of traffic, except if they are moving faster than the speed of walking – in that case, they should keep to the other side if appropriate.
- They may use a cycle track or path, but should not disturb the movement of cyclists.
- As a general rule, they should only be used on roads with a low traffic volume.
- They should wear appropriate protective equipment, including gloves, elbow/knee pads and helmets. They should also wear clothing or accessories that make them more visible, such as arm bands or belts made of fluorescent materials.

Users of recreational devices have not usually been seriously considered by policy makers in their considerations of transport options. This is an area that could be reviewed. Kick-scooters, for example, fit in between bicycles and pedestrians in the spectrum of active transport modes. They are slower and less efficient than bicycles, but as a result cause less conflict with pedestrians and thus may be more acceptable for shared use of pedestrian facilities.

2.3 Human-powered vehicles

The development of bicycle design has been constrained to a degree by the regulations of the bicycle racing community. More efficient designs have appeared at various times since the 1930s or earlier and have been banned from racing because of the perception that they constituted unfair competition. As a result, these designs were not developed further for more general use.

In the 1970s the International Human Powered Vehicle Association was formed to provide a forum for developing and racing these innovative designs. The only rules applying to an HPV are that it must be human powered and not have any form of energy storage. Because almost all of the energy required to propel a bicycle at higher speeds is used to overcome aerodynamic drag, most of the developments in HPV design have been aimed at reducing this. Typically, this is achieved by reducing the frontal area and by using fairings and body shells. Figures 2.2–2.7 below show examples of HPVs. These range from recumbent bicycles with modified geometry to achieve a lower riding position and hence reduced frontal area, to tricycles that can achieve an even lower position and provide stability when stationary. Aerodynamic aids range from windscreens through to fully enclosed body shells. The velomobiles shown in figures 2.6 and 2.7 are intended as substitutes for the car and offer a degree of luggage capacity and weather protection.

On flat ground, the efficiency gains achieved by HPVs are extraordinary. The one-hour world record for a cyclist on a bicycle that meets the current regulations[2] is 49.7km. The world record for an HPV is 87.1km.

[2] Various higher distances (up to 56.4km) have been achieved using bicycles that no longer meet the regulations. These are no longer official world records.

Clearly the HPV is much more efficient than a bicycle on flat ground. However, when going uphill, the bicycle is favoured. In this situation, weight is of critical importance. The fastest HPVs have a fully enclosed body shell and thus cannot be built as lightly as conventional bicycles. Downhill speeds depend primarily on aerodynamics, so in this situation the HPV is favoured.

Figure 2.2 Lightning P38 short wheelbase recumbent (en.wikipedia.org)

Figure 2.3 Easyracer long wheelbase recumbent (de Pont)

Figure 2.4 Long wheelbase recumbent with fairing (en.wikipedia.org)

Figure 2.5 Recumbent tricycle with fairing (en.wikipedia.org)

Figure 2.6 Alleweder KV4 velomobile (upload.wikimedia.org)

Figure 2.7 Flevobike Versatile velomobile (www.ligfietsshop.nl)

From a regulatory perspective, HPVs are not specifically identified but, in general, are considered to be bicycles and all the relevant regulations for bicycles apply. A few HPVs are in use in New Zealand, including one or two velomobiles. As far as we are aware, there are no issues relating to their legitimacy as road users. The maximum width for a bicycle in New Zealand is 1m. The tricycle HPVs and velomobiles can meet this width requirement. In the Netherlands the width of velomobiles seems to be an important issue. One manufacturer is quoted as stating that the optimal width is between 0.75m and 0.8m. The reason for this is that if the width is greater than 0.75m, the vehicles are not legally required to use mandatory cycle paths (conventional bicycles are not allowed on the road if there is a cycle path available). However, if they are wider than 0.8m, they will not fit through a standard door and hence are difficult to store inside.

This width factor is also relevant when considering policy issues. In New Zealand and Australia, the minimum recommended width for a cycle path is 1.5m although, in practice, some are narrower. A 0.8m-wide velomobile or recumbent tricycle would not be able to overtake a similar vehicle on a minimum-width cycle path without going over the edge. If the ‘edge’ is a painted line, this can be managed; if it is a kerb, this is a serious limitation. It should be noted that the same issue applies to bicycle trailers, which are often of similar width. In Europe, cycle paths are typically at least 2m wide and may be up to 3m wide.

2.4 Hybrids – power-assisted bicycles

Hybrid human-powered vehicles exist in all three of the sub-categories described above. The concept of fitting a small engine to a bicycle dates back to the beginning of the automobile. In 1885, Gottlieb Daimler fitted an engine to a wooden bicycle, thereby creating the first motorcycle. By the early 1890s, various inventors were fitting small petrol engines to bicycles, while the first patents for electric-powered bicycles in the US were filed in the mid-1890s. Many of the technologies used in modern electric bicycles, such as hub motors and friction drive, were patented in the 19th century. However, there seems to have been little further development of electric bike technology until the 1990s.

The use of small internal combustion engines (ICEs) on bicycles did continue through the 20th century, albeit at a relatively modest scale. The Solex company in France developed the VeloSolex powered bicycle in 1946 and sold more than 8 million units. The VeloSolex brand is now owned by an American company and the vehicle can still be purchased today. The current model, shown in figure 2.8, has a 49cc engine that produces 0.8hp (600W). It is speed-limited to 32km/h, and is claimed by the manufacturer to achieve a fuel consumption of 68–85km/l. It has an optional catalytic converter that can be fitted to the exhaust, but it makes no claim to meet emissions standards.

Figure 2.8 Current model VeloSolex 4800S (commons.wikimedia.org)

Figure 2.9 967 Honda P50 moped (www.vintagebike.co.uk)

Some mopeds, such as the Honda shown in figure 2.9, were effectively hybrids. This Honda has a power output of 900W, a top speed of 40km/h, and a claimed fuel consumption of 90km/l. Note that in both cases, the claimed fuel consumption and speed are for engine-only operation.

Various engine kits for fitting to bicycles are available on the market today. Two examples are shown in figures 2.10 and 2.11. The Redmax kit in figure 2.10 is a 25cc engine supplied by Golden Eagle in the US. They claim speeds of up to 50km/h and fuel consumption of over 100km/l. The rotary engine kit shown in figure 2.11 comes from Australia, and the suppliers claim a much more modest performance with a power output of 200W, a top speed of 24km/h, and a fuel consumption of 65km/l when travelling at 24km/h.

Although electrically assisted bicycles were first built in the 19th century, very few were built until the 1990s. The likely reason is that the battery packs required to provide a useful range were relatively heavy and therefore much of the benefit of the electrical assistance will have been offset by the additional weight. This is particularly true in hilly environments, where weight is an important factor in bicycle performance. The environmental movement and concerns about emissions and global warming have led to a major upsurge of interest in electric vehicles, particularly electric bicycles.

Figure 2.10 Redmax engine kit (www.bikeengines.com)

Figure 2.11 Rotary Australia engine kit (www.rotarybike.com)

Hybrid electric bicycles can be separated into two types, which are typically called the 'e-bike' and the 'pedelec'. The e-bike has a separate controller (usually a twist throttle) whereby the rider can control the amount of assistance provided by the electric motor. The pedelec has an electronic control system that controls the motor and provides assistance in proportion to the applied pedal loads. Thus the e-bike can be ridden without pedal assistance, while the pedelec cannot. Although many of the early models of electric bike were developed in the west (the US in particular), production in the west remains modest. Some of the major bicycle manufacturers, including Avanti in New Zealand, produce models with electric assistance, but only in small volumes. However, the technology has been taken up with enormous enthusiasm by the Chinese. Current reports indicate that there are now more than 40 million electric bicycles in use in China – although many of these are more properly regarded as electric vehicles rather than hybrids. This distinction will be discussed in the next section.

The specifications of electric bikes vary somewhat between jurisdictions because of regulatory requirements. In some countries they are limited in power to a maximum of 180W or 200W. In other countries they are limited by maximum speed, typically 32km/h. As a consequence, it is difficult to give typical performance characteristics. Maximum speeds are usually between 20 and 30km/h, although with pedal assistance it may be possible to exceed this. Many older designs used sealed lead-acid batteries. Newer designs tend to favour NiMH or Li-Ion batteries, which have higher energy density. Typically the amount of stored energy is between 250 and 500Wh which, depending on speed, rider weight, and whether the rider pedals, gives a range of 25–60km+ – that is, about 100–120km/kWh.

Prototype fuel cell-powered bicycles have been demonstrated at various exhibitions and shows, but as far as we are aware, none are yet in production. Essentially, a fuel cell uses a chemical process to convert hydrogen into electricity. The electricity is then used to drive an electric motor. Thus hydrogen fuel cell vehicles are really just electric vehicles with the fuel cell replacing the battery as a source of stored energy. In fact, because the hydrogen is normally generated by electrolysis (that is, by applying electricity), the hydrogen fuel cell behaves exactly like a rechargeable battery, except that the recharging can be done while the system is in use.

The regulatory framework under which hybrid bicycles operate varies considerably from country to country. In most places they are considered as bicycles and all the rules pertaining to bicycle use apply. However, the definition of what constitutes a power-assisted bicycle and what constitutes a powered vehicle varies considerably. In New Zealand, the definition of a power-assisted bicycle is given in the consolidated Land Transport (Road User) Rule (2004) issued in 2008 as ‘a cycle to which is attached one or more auxiliary propulsion motors having a combined maximum power output not exceeding 300 watts’. The Land Transport Act (1998) was modified so that the Director of Land Transport could declare that vehicles with a power output less than 600W were not motor vehicles. Accordingly, the Director issued a Gazette Notice on 2 February 2006, declaring that power-assisted pedal cycles that were powered by a motor with a maximum power output not exceeding 300W were not motor vehicles. The situation for vehicles with a power output between 300W and 600W remains unchanged until operating conditions for these vehicles can be resolved.

This is a more liberal power allowance than that in many countries. Australia, for example, allows a maximum power of 200W. In Europe, only pedelec types are considered bicycles, and these are restricted to a maximum power of 250W and a maximum speed under assistance of 25km/h (that is, the electric motor must cut out when the speed exceeds 25km/h). E-bikes are not considered to be bicycles, and thus the licensing rules for mopeds apply to them. In Canada and the US, the maximum power requirements are more liberal (500W in Canada and 750W in the US) but a maximum assisted speed of 32km/h applies. In practice, the situation in Canada and the US is more complex because although these are the national rules, the provinces and states can and do make their own rules, which differ from these.

The classification of a power-assisted bicycle is important for a number of reasons, including the right to use bicycle facilities; the minimum legal age of the rider; requirements for driver licences; requirements for vehicle registration; requirements for periodic inspections; and even the type of helmet required.

There appears to be very little policy work in New Zealand related to power-assisted bicycles, other than the regulatory issues discussed above. In California, where there are financial incentives for the purchase of low-emission vehicles, electric-powered bicycles qualify. Generally, power-assisted bicycles, particularly those with electric motors, produce very low emissions and for many people, could expand the number of trips for which cycling is an option.

2.5 Hybrids – power-assisted recreational devices

Many of the recreational human-powered vehicles reviewed above are also available in powered form, with either petrol-powered ICEs or electric motors providing the power. Examples include scooters and skateboards. The consolidated Land Transport (Road Users) Rule (2004) issued in 2008, which established the definition of recreational wheeled devices, specifies that they may have auxiliary propulsion motors with a combined power of up to 300W. If the power of the propulsion system is greater than 300W, then under current New Zealand regulations these vehicles are mopeds and as such should be registered, and used only on the road by a licensed driver wearing an approved helmet. As the engine of these recreational devices is usually less than 600W, there is provision for the Director of Land Transport to gazette them as 'not a motor vehicle'. However, as far as we are aware, this has not been done for any of these vehicles.

In practice, the power of the motors on these vehicles almost always exceeds 300W, and in most cases, 600W. Go-Ped, which is a well-known brand of powered scooters, offers nine models of scooter on their New Zealand website, comprising two electric models, two human-powered-only models and five petrol-powered models. The petrol-powered models have power ratings between 1.5hp and 4.5hp (1120W–3360W). The power of the electric motor is not quoted on the New Zealand website, but the company's California website states that the electric motor is capable of over 1hp (750W) continuous output. Similarly, the electric skateboard being offered by E-ride in New Zealand is advertised as having an 800W motor.

Where these vehicles are petrol-powered, the engines are typically small (25–50cc) two-stroke motors. Two-stroke motors are light and generally have quite good power-to-weight ratios, but have poorer fuel efficiency and emissions performance than four-stroke motors. On its US website, Go-Ped claims a fuel economy of 100mpg (42.5km/l) for several of its scooters. The electric-powered vehicles produce no emissions in use, but we do need to consider the emissions resulting from power generation. Go-Ped claims a range of 14 miles (22.5km) for its electric scooter in economy mode from a battery pack with a capacity of 400Wh (56km/kWh). The E-ride skateboard reportedly has a range of 20km+ from a battery pack with a capacity of 430Wh (46.5km/kWh).

The regulatory environment in New Zealand does cover these vehicles, although there appear to be relatively few of them operating here. In most cases they should be classified as mopeds, and thus should be registered and driven on the road by a licensed driver. In practice, these requirements are widely ignored. Internationally, this situation appears to be quite common (Police Service of Northern Ireland 2006). In California, the use of nearly all petrol-powered scooters is effectively banned, because very few of them can meet the required emission standards (UrbanScooters.com 2003).

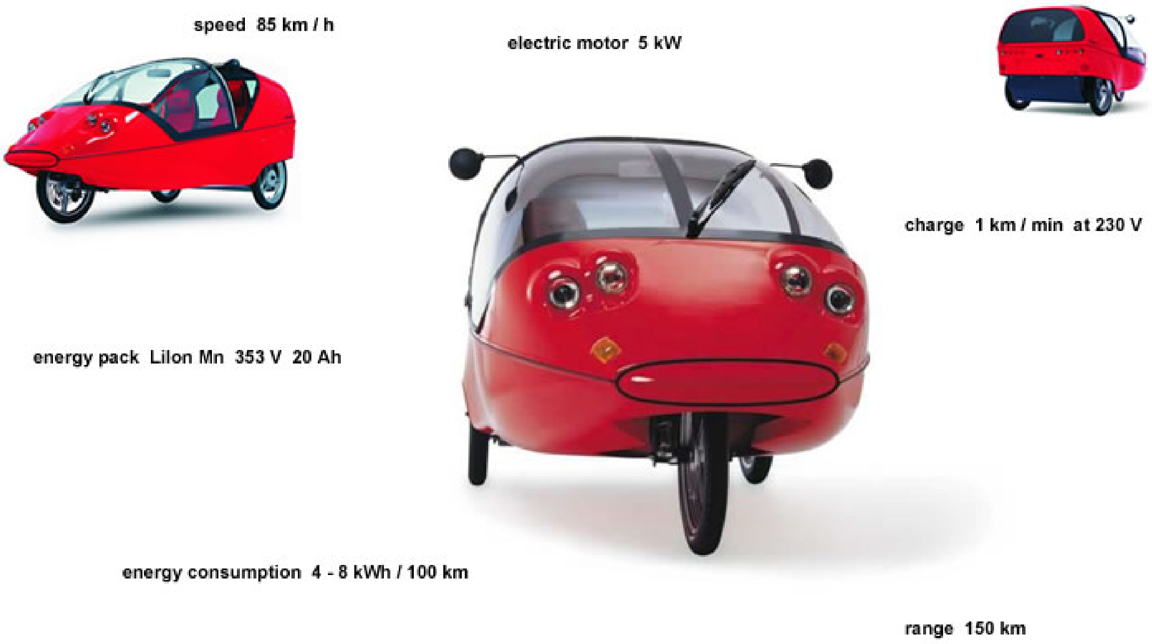
The issue of powered recreational devices being used for transport does not appear to have received much attention from policymakers.

2.6 Hybrids – power-assisted HPVs

The final category of hybrid human-powered vehicles we will consider are the HPVs. Some of the HPVs illustrated earlier in figures 2.2–2.7 are available with electric power assistance. In fact, because there are a range of electric assistance kits available for fitting to bicycles, virtually all HPVs can be converted to human-powered hybrids. There are some velomobile-style HPVs that are only available as hybrids, such as the Aerorider shown in figure 2.12. One of the more interesting hybrid human-powered vehicles is the two-seater Twike shown in figure 2.13.

Figure 2.12 Aerorider hybrid electric velomobile (www.vkblog.nl)

Figure 2.13 Twike two-seater hybrid (www.ubergizmo.com)



The Twike was originally designed in 1986, by a group of Swiss students, as a human-powered vehicle. The second version of the vehicle (in 1991) was a hybrid electric–human-powered vehicle. The designers then formed a company and tried to commercialise the vehicle. Production of the third design variant commenced in 1995. In 2002, the ownership of the design was taken over by a German company and production continues to this day. The vehicle is available as either a hybrid electric–human-powered vehicle, or as electric power only. Although relatively expensive (prices start at €20,500 and can exceed €35,000), there is a waiting list of around six months. All of the velomobiles shown in the previous discussion also have long waiting lists.

The Aerorider quotes a range of 20–80km, depending on operating conditions and the size of the battery pack. The smallest battery pack option has about 400Wh, so the energy is upwards of 50km/kWh. Note that although this is similar to the electric scooters and skateboards above, a velomobile would generally be operating at higher speeds where more power is required. The Twike, which is a much bigger vehicle, quotes an energy consumption of 20km/kWh. However, the Twike is capable of a top speed of 85km/h and would normally be operating at car traffic speeds.

From a New Zealand regulatory point of view, the Twike has a 5kW motor and has a top speed well in excess of 50km/h; thus, it is a motor tricycle. It must be registered and pass a warrant of fitness inspection. The situation regarding the class of driver licence required and type of helmet to be worn is not clear. The principle for three-wheelers appears to be that if it has motorcycle-style controls (handlebars), then a motorcycle licence and helmet are required; whereas if it has car-style controls (a steering wheel), then a driver licence and safety belts are required, but not helmets. The controls on the Twike are in neither of these categories, but it would seem to better fit the second option.

The Aerorider has a 600W motor and a maximum speed of 45km/h. Thus it would qualify as a moped requiring registration, and the rider would need a driver licence. Alternatively, it could be classified as ‘not a motor vehicle’ by the Director of Land Transport, and allowed to operate subject to some conditions. If it was registered as a moped, the rider would be required to wear an approved motorcycle helmet. However, the vehicle is a human-powered hybrid. For optimum operation the rider needs to pedal, and wearing a motorcycle helmet would severely limit his or her ability to do this because of overheating. If the Director approved it as 'not a motor vehicle' and allowed it to operate under the same conditions as a power-assisted bicycle (that is, a bicycle helmet is required) these difficulties would be overcome.

This situation is likely to apply to other hybrid velomobiles. The aerodynamic efficiency of their body shells means that they can achieve relatively high speeds (for the amount of human effort applied) on flat ground and downhill. On an uphill gradient, the amount of effort required is primarily determined by weight, and these vehicles are quite heavy compared to bicycles (even more so when fitted with an electric motor and batteries). The amount of power assistance required to maintain reasonable speeds uphill is quite high, and therefore the desirable motor power is likely to be higher than 300W.

Government policy relating to this type of vehicle is very limited. The vehicles only exist in very small numbers worldwide, and thus there has been little demand for specific policy.

3 Low-powered urban vehicles

3.1 Introduction

There is some overlap between the vehicle types reviewed in this section and the hybrid vehicles considered in the previous section, in that some of the vehicles in this section have provision for human-powered propulsion. For example, some mopeds are fitted with pedals. The distinction that we have made between the two categories is that vehicles in this section are not primarily intended to be propelled by human power and are not really designed for it.

The following three broad sub-categories can be defined:

- mobility and recreational devices that are primarily designed for footpath use
- mopeds, which include two- and three-wheeled vehicles that are designed for on-road use
- quadricycles and neighbourhood electric vehicles, which are four-wheeled vehicles designed for on-road use.

The last two sub-categories are distinguished from conventional motorcycles and automobiles by having some concessions on the requirements for their use and being subject to some special operating conditions.

3.2 Mobility and recreational devices

As the population ages, mobility scooters are becoming increasingly popular for local transport. These vehicles are usually electrically powered, and have either three or four wheels. Typical examples are shown in figures 3.1 and 3.2 below. The three-wheeled configuration is typically lighter and more manoeuvrable than the four-wheeled configuration, but is less stable. Thus, if the scooter is to be regularly transported in the back of a car, or is to be used extensively indoors, such as in shopping malls, the three-wheeler has some advantages; if the vehicle's main function is transport, the four-wheeler has benefits.

Figure 3.1 Three-wheeled mobility scooter (electricscootershome.com)

Figure 3.2 Four-wheeled mobility scooter (www.easymobilityco.com)

These scooters range in weight from about 50kg to over 150kg. One of the main factors in determining the weight is the size of the batteries, and thus the lightweight scooters have smaller battery packs and less range. Range varies from about 10km to over 40km. Maximum speed varies from about 7km/h to about 19km/h. Some, like the model shown in figure 3.2, are fitted with lights, indicators and stop lights.

The 'mobility devices' category also includes powered wheelchairs. These have a different target market from scooters. Scooters are aimed at people with reduced mobility. Powered wheelchairs are aimed at people with severely impaired mobility and usually insufficient strength to propel a manual wheelchair. The wheelchairs have greater manoeuvrability because they need to access a much wider range of locations. They generally have maximum speed in the range of about 5.5–10km/h.

Recreational devices include vehicles like the Segway shown below in figure 3.3. The Segway has a maximum speed of 20km/h and a range of 26–39km. The power output of the motor is not given, but based on the capacity of the battery packs and the vehicle's potential speed and range, it would appear to be about 400W. Other vehicles in this category include some electric kick-scooters, which are clearly not designed for human-powered propulsion even though it may be theoretically possible.

Figure 3.3 Segway personal transportation device (commons.wikimedia.org)

The Land Transport (Road Users) Rule (2004) defines mobility devices and specifies rules for their use. The definition of a mobility device is as follows:

> *mobility device means a vehicle that is designed and constructed (not merely adapted) for use by persons who require mobility assistance due to a physical or neurological impairment.*

It also defines a wheeled recreational device:

> *wheeled recreational device—*
>
> *a) means a vehicle that is a wheeled conveyance (other than a cycle that has a wheel diameter exceeding 355 mm) and that is propelled by human power or gravity; and*
>
> *b) includes a conveyance to which are attached 1 or more auxiliary propulsion motors that have a combined maximum power output not exceeding 300 W.*

Furthermore section 11.1 of the Rule is as follows:

> ***11.1 Use of footpath and roadway***
>
> *1) A pedestrian must, at all times when practicable, remain on the footpath if one is provided.*

2) *A driver must not drive a mobility device on any portion of a roadway if it is practicable to drive on a footpath.*

3) *A pedestrian or driver of a mobility device or a wheeled recreational device using the roadway must remain as near as practicable to the edge of the roadway.*

4) *A driver of a mobility device or wheeled recreational device on a footpath—*

   (a) must operate the device in a careful and considerate manner; and

   (b) must not operate the device at a speed that constitutes a hazard to other footpath users.

5) *A person using a wheeled recreational device on a footpath must give way to pedestrians and drivers of mobility devices.*

6) *A pedestrian must not unduly impede the passage of a mobility device or wheeled recreational device on the footpath.*

Some distributors of recreational devices claim that their vehicles can operate under these provisions and hence can be driven on footpaths without a licence. However, in most cases, recreational devices have motors that have a maximum power output greater than 300W and cannot be construed as being designed and constructed for users whose mobility is impaired. This would suggest that these devices should be classified as mopeds and hence operate on the road, be registered and require a driver licence.

In the UK, the regulations distinguish between two classes of mobility scooter:

- Class 2 mobility scooters are intended for use on the footpath only and have a maximum speed of 4mph (6.4km/h).
- Class 3 mobility scooters are permitted on the road, have a maximum speed of 8mph (13km/h) and must be registered.

Class 3 scooters sold in the UK can be switched down to the 4mph maximum speed for footpath use. The UK regulations also specify that these vehicles may only be used by people suffering from a disability.

In the Netherlands, mobility scooters are permitted to operate on footpaths, cycle paths, or roads when no cycle path is available. Speed limits are 45km/h on roads, 30km/h on cycle paths and 6km/h on footpaths. No driver licence is required, but the rider must be over 16 years of age unless the maximum vehicle speed is less than 10km/h. The vehicle must be insured.

The use of Segways and similar recreational vehicles on public infrastructure is quite restricted in many jurisdictions. This is largely because of difficulties in classifying the vehicle. In some jurisdictions they are treated as mopeds and required to be fitted with indicators, lights and sometimes a mechanical brake. Segways have often been used on footpaths, but this causes concern because of their relatively high speed compared to other pedestrians, and hence a number of jurisdictions have banned them.

Policy positions relating to mobility scooters and recreational vehicles are also mixed. In many jurisdictions, mobility scooters are seen as very important in helping elderly and disabled people to achieve a degree of mobility and independence. However, there are safety concerns relating to the relative speed of the scooters compared to the other users of the infrastructure. In particular, if they are used on footpaths they should not be too much faster than pedestrians, while if they are used on cycle paths or the road they should not be too much slower than the other traffic. The safety issue is further complicated by the fact the mobility scooter rider is generally physically impaired in some way, and may have slower reactions and will be more susceptible to injury in the event of a crash. These trade-offs result in very different policy approaches. For example, New Zealand users of mobility scooters are encouraged to use only the footpath and consequently to operate at low speeds (4–6km/h) and travel relatively small distances. In the Netherlands, mobility scooters are used extensively on cycle paths and operate at relatively high speeds (15km/h +) and travel quite large distances.

The policy position with regard to recreational vehicles does not have the same element of social good. Thus the concerns regarding safety and relative speeds still apply, but not the benefits of providing mobility to people who would otherwise not have it. It is easy to see why jurisdictions are generally not actively encouraging these vehicles.

3.3 Mopeds

Mopeds initially came into existence as hybrid bicycles (see section2.4) but have since evolved into essentially being light motorcycles. They continue to exist as a separate class of vehicle in many jurisdictions. Generally, they are limited in engine size and/or power, and often in maximum speed. They often have restricted access to the infrastructure; for example, they are not allowed to use motorways, and in many countries do not require the same level of driver licence as a motorcycle.

In New Zealand, a moped is limited to an engine capacity of less than 50cc, an engine power of less than 2kW and a maximum speed of less than 50km/h. The vehicle must be registered but does not require a warrant of fitness. The rider must hold a driver licence of any class and must wear a motorcycle helmet. A moped must be used on the road (not on a footpath or cycle path), but may not be used on motorways. This set of conditions is typical of those required in other jurisdictions, although there are many variations.

Some jurisdictions have two classes of moped with different maximum speeds. For example, in the Netherlands, the ‘snorfiets’ is limited to 25km/h, while the ‘bromfiets’ is limited to 45km/h. The two categories have different requirements and restrictions. Belgium, Denmark and Sweden similarly have two classes of moped.

Driver licence requirements vary, from none (in Sweden, anyone over the age of 15 may ride a class 2 moped) through to a car or motorcycle licence as in New Zealand. Many jurisdictions have special moped licences that can often be attained at a younger age than car or motorcycle licences.

The vehicle performance restrictions also vary considerably. Some jurisdictions require a moped to be fitted with pedals that can be used to propel the vehicle. Some require that the vehicle does not have a rider-operated clutch or transmission. Engine size limits vary, although the 50cc upper limit is widespread. Maximum allowable speed capability varies substantially, from as little as 25km/h up to 75km/h. The most common limits are 45km/h and 50km/h. Engine power limits also vary. Some jurisdictions have no power limit (as in Finland) while others vary between 1kW and 4kW.

Most mopeds have two-stroke engines. Typically, these do not have good emissions performance, although this is being addressed to a degree with new technologies. A small number can now meet the Euro 3 requirements. We are not aware of any meeting the Euro 4 standard. However, this is a problem with the engine technology, not with the moped concept itself. Honda, for example, has always used four-stroke engines for its mopeds, and these can be made compliant with the Euro 3 and 4 emissions standards.

A study in Denmark (Saxe 2003) argues that the current tax concessions for mopeds should be withdrawn. This argument is based primarily on their poor emissions and safety performance. Saxe claimed that mopeds produced far more particulate and hydrocarbon emissions per kilometre than cars. There are two classes of moped in Denmark, which he called moped-30 and moped-45 (the number reflecting the maximum legal speed). Moped-45s have a similar serious-injury and fatal-crash rate to motorcycles, which is 50 times higher than that of cars. Moped-30s have a crash rate that is 1.5 times higher again – possibly because they may be used by anyone over the age of 16 with a special moped licence. In Denmark, one must be 18 years old to obtain a car or motorcycle licence and the costs of running a car are very high, while the costs of running a moped are low. Thus the moped-30 is the vehicle of choice for teenagers. Saxe found that two-thirds of the riders of moped-30s were aged between 16 and 20.

These arguments are less valid in New Zealand. The injury and fatal-crash rate for mopeds is significantly lower than that of motorcycles. In 2006, there were 57,048 motorcycles and 18,123 mopeds registered for use on the road. Over that year there were 772 injury and 37 fatal crashes involving motorcycles, while there were 179 injury and no fatal crashes involving mopeds. There may be some differences in exposure (annual kilometres travelled), but this is not known. It is more likely that the main reason for the difference is the speed environment and the actual speeds at which the vehicles operate. Mopeds are used almost exclusively in urban environments, where the speed limit is usually 50km/h, and the maximum speed of the moped is 50km/h. Motorcycles are used in both urban and open-road environments.

3.4 Quadricycles, neighbourhood electric vehicles and kei cars

European regulations include a four-wheel equivalent of the moped, which they call a ‘quadricycle’. These vehicles typically look like small cars. They are restricted in weight and power and are not required to meet all of the safety performance standards that standard cars must meet. In some jurisdictions, the driver licence requirements for quadricycles are less rigorous than those for cars. The US regulations do not explicitly allow quadricycles, but Federal Motor Vehicle Safety Standard 500 (FMVSS 500) provides for a low-speed vehicle classification with less-stringent safety requirements than those for normal cars. It is up to individual states to decide what FMVSS 500 vehicles they permit on which roads. The classification has mainly been used for neighbourhood electric vehicles (NEVs) in restricted speed environments.

European quadricycles are split into two categories. Light quadricycles have a maximum tare weight of 350kg[3], a maximum engine power of 4kW and a maximum speed of 45km/h. These restrictions are very similar to those for the standard European moped, and thus essentially this category allows for mopeds to have four wheels. The standard quadricycle has a maximum tare weight of 400kg[3] and a maximum engine power of 15kW. Quadricycles designed for the transport of freight are permitted a maximum weight of 550kg. The quadricycle was a French development of the 1970s, and the main producers are still French, although there are also manufacturers in Italy, Germany and the Netherlands.

Most quadricycles have the appearance and function of a small car, and all of the early models were powered by small petrol or diesel engines. Figures 3.4 and 3.5 show two current models of quadricycle that are powered by ICEs. More recently, electric-powered quadricycles have become available. Two examples are shown in figures 3.6 and 3.7. Although the regulations were introduced to enable the continued operation of the micro-car style of quadricycle, they also allow for the four-wheel motorcycle to be made a road-legal vehicle, as shown in figure 3.8. Applications of quadricycles go beyond personal transportation, and the regulations provide for small freight vehicles as shown in figure 3.9. This particular example is available with either diesel or electric power options.

[3] For electric vehicles, this maximum weight does not include the weight of the batteries.

Figure 3.4 Chatenet S2 light quadricycle (www.automobiles-chatenet.com)

Figure 3.5 Chatenet Speedino standard quadricycle (www.qdoscars.co.uk)

Figure 3.6 Aixam-Mega City electric quadricycle (commons.wikimedia.org)

Figure 3.7 Reva G-Wiz electric quadricycle (en.wikipedia.org)

Figure 3.8 Road-legal quadricycle (shop.ramquads.com)

Figure 3.9 Mega Multitruck quadricycle (en.wikipedia.org)

Light quadricycles are limited to a maximum speed of 45km/h, but there is no such restriction on standard quadricycles. The Chatenet Speedino shown in figure 3.5 is fitted with a two-cylinder, 505cc, 15kW petrol engine, and has a claimed top speed of 100km/h and a claimed fuel economy of over 20km/l. The diesel-powered options typically have superior fuel economy. The Aixam 751 diesel specifications quote a fuel economy of 25km/l, compared to 20km/l for the Aixam 751 petrol. Light quadricycles have less power and generally achieve still better fuel economy. The Ligier X also has a quoted fuel economy of over 31km/l. Electric-powered quadricycles typically have a range of 60–80km and an energy consumption of about 8–9km/kWh.

The regulations regarding road tax and driver licence requirements vary considerably from country to country. Light quadricycles are considered to be similar to mopeds. In Italy and Spain they can be driven by anyone over 14 years of age without a driver licence, although they must pass a highway code theory test. This also means that people who cannot obtain a driver licence, such as those with failing eyesight, or disqualified for drunk-driving, can still legally drive a quadricycle. In France they may be driven by anyone over 16 years of age. A special quadricycle road safety certificate was introduced in 2004 as a requirement, but this does not apply retrospectively and thus anyone who was already 16 or older in 2004 is not required even to pass this test. Germany has a special licence class for quadricycles that has a minimum age of 16 years. The UK originally had provisions that allowed quadricycles to be driven with a motorcycle licence. This was changed in 2001 so that a full car licence is now required. Again, the change was not retrospective, so anyone who held a motorcycle licence in 2001 can continue to drive a quadricycle on this licence.

Road taxes are similarly variable. Some European countries have road tax rates based on engine capacity and/or vehicle weight, which result in favourable rates for quadricycles. In the last few years some countries, including the UK, have introduced road taxes based on CO_2 emissions, which should favour quadricycles. However, in the UK quadricycles are not considered cars and are not included in the emissions-based registration system. On the other hand, in the UK electric-powered quadricycles qualify as zero-emissions vehicles, and are exempt from road tax and also from the London congestion charge.

The European regulations on quadricycles (EC 2002) specify a number of safety requirements (safety belts, lights, indicators, wipers, brakes and so on), but exempt them from the crashworthiness testing requirements. In the UK this has become a contentious issue. In 2007 a popular television motoring show organised for a standard frontal-impact crash test to be conducted on a Reva G-Wiz. The vehicle performed rather badly and it took half an hour to remove the crash dummy from the vehicle, with the extraction process requiring the legs to be removed from the torso. The test was undertaken at a higher speed than specified by the standard (64km/h, rather than 56km/h), and this would have significantly increased the energy of the crash, but nevertheless the outcome was severe. As a result, the UK government requested that the European Union review the safety requirements of quadricycles. At the time of writing, these had not been changed.

Various advocates for electric vehicles, including the company distributing the Reva, responded with a number of points that should at least be considered. The first is that the Reva is a low-speed urban vehicle that typically operates in traffic environments where vehicle speeds are low. The average speed for a G-Wiz operating in London is 16km/h. Should they be expected to meet the same crashworthiness requirements as cars designed for highway speeds of 120km/h or more? The safety record of quadricycles is generally very good. In Europe they have less than one-third of the crash rate (per 100,000 vehicles) of ordinary cars. In the UK, these vehicles have recorded more than 32 million kilometres travelled with no fatal or serious crashes. Other urban vehicles, such as mopeds, are also not required to meet crashworthiness standards. Since this crash test was undertaken, a new model of G-Wiz has been released and was successfully crash tested at 40km/h, which is slower than the standard speed.

The Aixam and Mega quadricycles, which are produced by the same French company, have been crash tested voluntarily since 1988 and meet all the requirements for conventional cars. Figure 3.10 shows photographs (of an Aixam in the Netherlands that had been hit from behind by an Audi A6, which was estimated by the police to have been travelling at 100km/h. The driver of the Aixam walked away from the crash with minor bruising. Clearly, the occupant protection systems of this vehicle performed very well in this instance. Thus, although all current quadricycles do not meet the crashworthiness requirements imposed on conventional cars, there is no technical reason why they could not do so if it was required.

Figure 3.10 Aixam hit from behind by an Audi A6 travelling at 100km/h (www.rijnders-minicars.nl)

The US does not permit quadricycles as defined by the European regulations, but does have provisions in federal regulations for low-speed vehicles (LSVs). LSVs are limited to a maximum weight of 1361kg and a maximum speed of 40km/h. In addition, the vehicle must be able to accelerate from 0 to 32km/h within 1.6km. The vehicle must be fitted with 10 specified items of safety equipment, including lights, reflectors, indicators, mirrors, windshield, seatbelts and parking brake. There are no crash-testing requirements. A full driver licence is required to operate an LSV.

Although the LSV requirements are specified by federal regulations, the conditions under which LSVs can operate are set by the individual states. The LSV regulations do not specify the means of propulsion, but in practice, most LSVs are electrically powered and known as neighbourhood electric vehicles (NEVs). A Canadian study (Lamy 2002) reported that some 30 states had authorised the use of LSVs, mostly on roads with a speed limit of 56km/h (35mph) or less. Thirteen of these states had limited the authorisation to electric vehicles only. NEV supplier websites indicate that more than 40 states have now approved NEVs. Even with state authorisation, municipalities can further restrict the use of LSVs within their area.

The Canadian federal authorities have adopted the US LSV requirements, but limited their application to electric vehicles. As with the US, the Canadian provinces have full discretion as to the conditions under which they will allow LSVs to operate within their jurisdiction.

As can be seen from the requirements described above, NEVs are restricted to a lower speed limit than light quadricycles, but have a much higher maximum weight and there are no restrictions on power. This means that it is possible to build NEVs that are larger than quadricycles, with more carrying capacity. Genuine four-seater models are widely available. Broadly, NEVs fall into two categories: car-like vehicles that are similar to European quadricycles in appearance; and golf cart derivatives. Two examples of each category are shown in figure 3.11. Because the weights are typically higher than quadricycles, NEVs tend to have a shorter range; 40–60km is typical. The energy consumption is also typically slightly higher.

Various federal and state incentives have been offered for alternative-fuel vehicles, including NEVs. These vary significantly from state to state, but they can be substantial. In 2005, a federal tax credit of 10% (with a maximum of $4000) of the purchase price was offered to anyone buying a qualifying new electric vehicle. This tax credit has since been phased out. California, which has the most serious air pollution problems in the US, has numerous incentives for zero-emission vehicles, including rebates to purchasers of up to $5000. The biggest rebates are for the most expensive vehicles and, for example, a Miles ZX40 NEV, which is the vehicle shown in the top right corner of figure 3.11, is eligible for a rebate of $1500. This car sells for $18,000–$22,000 depending on options, so the rebate represents about 7–8% of the purchase price.

Figure 3.11 Examples of US neighbourhood electric vehicles (en.wikipedia.org, www.westerngolfcar)

Japan has long had a category of cars known as kei cars, which are restricted in vehicle size, engine size and power. The limits have changed over the years, but current requirements are as follows:

- maximum length 3.4m
- maximum width 1.48m
- maximum height 2m
- maximum engine size 660cc
- maximum engine power 47kW.

These vehicles are incentivised through tax concessions, and most of the major Japanese car manufacturers produce vehicles in this category. Kei cars are not limited to passenger cars, but also include a range of small vans and trucks. In Japan, kei cars represent 35% of new car sales.

Apart from these size and engine power restrictions, kei cars are considered to be normal cars, and are allowed full access to the road network and required to meet all the same safety and emissions standards as other cars. Almost all current kei cars are petrol powered. However, they are also the platform for electric cars that are currently under development. The Mitsubishi i MiEV electric car, which is due to go to market in 2009, is based on a kei car, the Mitsubishi i-car, which is currently available with a petrol engine.

Fuel economy figures are typically given as 16–25km/l. Some commentators have claimed that the small engine has to work too hard at highway speeds and consequently, the fuel economy at these speeds is inferior to that of other small cars with larger (1000cc) engines. This claim is very difficult to prove or disprove. Clearly, if we compare different vehicles, there are other factors that could have more effect than the change in engine size and power. There are some models of kei car with larger engines that are sold in other markets. For example, the Suzuki Alto is sold as a kei car in Japan, but is sold in Europe with a one-litre engine. However, we have not been able to find comparable fuel consumption test results for the two models – there are differences between the Japanese and European test procedures and the results are not directly comparable. It is indisputable that kei cars have good fuel economy. It may be that similarly sized cars with slightly larger engines have better fuel economy at highway speeds. Some further investigation is required.

Figure 3.12 A range of kei cars (en.wikipedia.org, motorfetish.files.wordpress.com)

4 Standard vehicles

4.1 Introduction

A number of different factors affect the fuel efficiency and emissions performance achieved by motorcycles and automobiles. In this section, we discuss the factors involved for standard vehicles – that is, motorcycles, motor tricycles and automobiles that have access to the full road network and are not subject to any special restrictions. The boundaries between these vehicles and those discussed in the previous section are a little blurred, and there is possibly some overlap. For example, one could debate whether kei cars should have been included here rather than in the previous section. As long as we don't overlook any significant vehicle types, this does not matter.

The key factors affecting fuel efficiency and emissions performance are:

- vehicle size and weight
- vehicle design
- engine performance
- fuel type (motive power).

In discussing these issues, we need to bear in mind not only existing technology, but also future directions. Concerns over the long-term supply of oil-based fuels have led to considerable research investment into alternative fuels and technologies. A number of these have been demonstrated at the prototype level but have yet to be proven at the production level. In determining appropriate policy, we need to assess the likelihood of these alternatives becoming available and the time frame for that.

4.2 Motorcycles

The first ICE-powered vehicle was a motorcycle built by Gottlieb Daimler in 1885. The first four-wheeled motor vehicle followed a year later. Note that steam-powered road vehicles were invented more than 100 years prior to this in 1769, and many people regard these as the first automobiles.

For most of the 20th century, motorcycles were used as a cheaper alternative to a car. In many Asian countries this is still the case. Following World War 2, there was a boom in motorcycle numbers with the development of the Japanese motorcycle industry and the advent of Italian motor scooters. In New Zealand in the 1960s and 70s, motorcycles were widely used as the main means of transport for young people and particularly students. With the introduction of cheaper second-hand Japanese import cars, as well as safety concerns and the reduction in petrol price in real terms, motorcycle use by young people in New Zealand declined through the 1980s and 90s. There has been a modest resurgence in motorcycle use in recent years because:

- people who were young in the 1960s and 1970s are buying large, modern motorcycles for recreational use
- recent fuel price increases, combined with road congestion, have made the small motorcycle or scooter an attractive option for commuting.

With few exceptions, motorcycles are petrol powered. Engine sizes range from 50cc to 2300cc. A 50cc motorcycle is not necessarily a moped because it may make too much power and have too high a maximum speed. Motorcycles with engines much larger than 2300cc have been built, but only in limited numbers. Motorcycle weights vary from about 70kg up to 450kg. Claimed fuel consumption ranges from less than 13km/l to over 40km/l. Many of the larger machines are built for performance and produce relatively high levels of power output, but are not particularly fuel efficient.

From an emissions perspective, one of the critical engine technology issues is the combustion cycle (two-stroke or four-stroke). Traditionally (50 years ago or more), two-stroke engines were primarily used for smaller (and cheaper) motorcycles. The two-stroke engine was simple, light, and produced higher specific power at the expense of some fuel efficiency. With the expansion of the Japanese motorcycle industry in the 1960s and 1970s, larger and more sophisticated two-stroke engines appeared. These produced high specific power outputs and performance, but at the expense of fuel efficiency. In recent times, the trend has gone back to using four-stroke engines for the larger and more powerful machines, and two-stroke engines for smaller engine capacities, although some of these two-stroke motorcycles still produce very high power outputs, particularly when their relatively low weight is taken into account. With the advent of emissions performance requirements, the use of two-stroke engines for motorcycles is likely to decline further because of the difficulties in meeting those standards.

Some alternative fuel and engine technologies have been used, but to date, these have either been prototypes or are only available in very small numbers. For example, gas turbine and jet-powered motorcycles have been built and are available in limited numbers. These are high-power-output vehicles, rather than fuel-efficient or low-emissions vehicles, and hence are not relevant to this study. Prototype electric, hybrid and fuel cell bikes have been built, and some are claimed to be close to market. Diesel motorcycles have also been built. Most of these are petrol-powered motorcycles that have been re-engined by enthusiasts, although there is an example of one that has been modified by the US army.

In many jurisdictions, the motorcycle is treated more favourably than the car in terms of registration fees, annual vehicle licensing costs, and so on. This is not the case in New Zealand, because the annual licensing fee includes an Accident Compensation Corporation levy, and motorcycles have a poorer safety record than cars. In congested traffic environments, the motorcycle has advantages and is often given further benefits through favourable regulations. For example, in London, motorcycles are exempt from the London congestion charge while in Auckland, motorcycles are permitted to use the designated bus lanes on the main arterial routes.

Typically, motorcycles are subjected to less rigorous safety and emissions requirements. For example, in most jurisdictions, the occupant protection requirements mean that a car needs to have a crumple zone at the front, side intrusion bars, airbags, and safety belts that the occupants are legally required to wear. Often, the only comparable requirements for a motorcycle are that the rider and passenger must wear an approved safety helmet. Although in the past motorcycles have not been required to meet the same emissions standards as cars, this is changing. At the time of writing, cars in Europe were required to meet the Euro IV standard, while motorcycles were only required to meet the Euro III standard. The differences in requirements were in part a reflection of how difficult it would be to make a motorcycle that complies with the higher standards.

Over the last 50 years, the number of motorcycles registered in New Zealand has fluctuated substantially, as shown in figure 4.1, which is derived from the Ministry of Transport (2008c). Total per-capita motor vehicle numbers over that period have grown steadily and are not showing any signs of flattening off. Per-capita motorcycle numbers underwent a period of substantial rapid growth through the 1970s, followed by an equally dramatic decline in the 1980s. Current levels are comparable to that of the 1960s, and are showing a slight upward trend, as they were then. It is difficult to fully explain the 1970s peak. Data from the San Francisco area shows a similar trend, so it would appear not to be specific to New Zealand. This was the heyday of the Japanese motorcycle industry, and Japanese motorcycles were relatively cheap. One might have thought that the 1973 oil shock could have led to drivers moving from cars to motorcycles, but the data shows a dip in numbers immediately after 1973. One might also have thought that the advent of cheap second-hand Japanese import cars could have contributed to the decline in motorcycle numbers, but the decline began in 1982 and the New Zealand market was not opened up to second-hand Japanese car imports until 1987.

Figure 4.1 Comparison of motorcycles per capita with vehicles per capita (derived from Ministry of Transport 2008c)

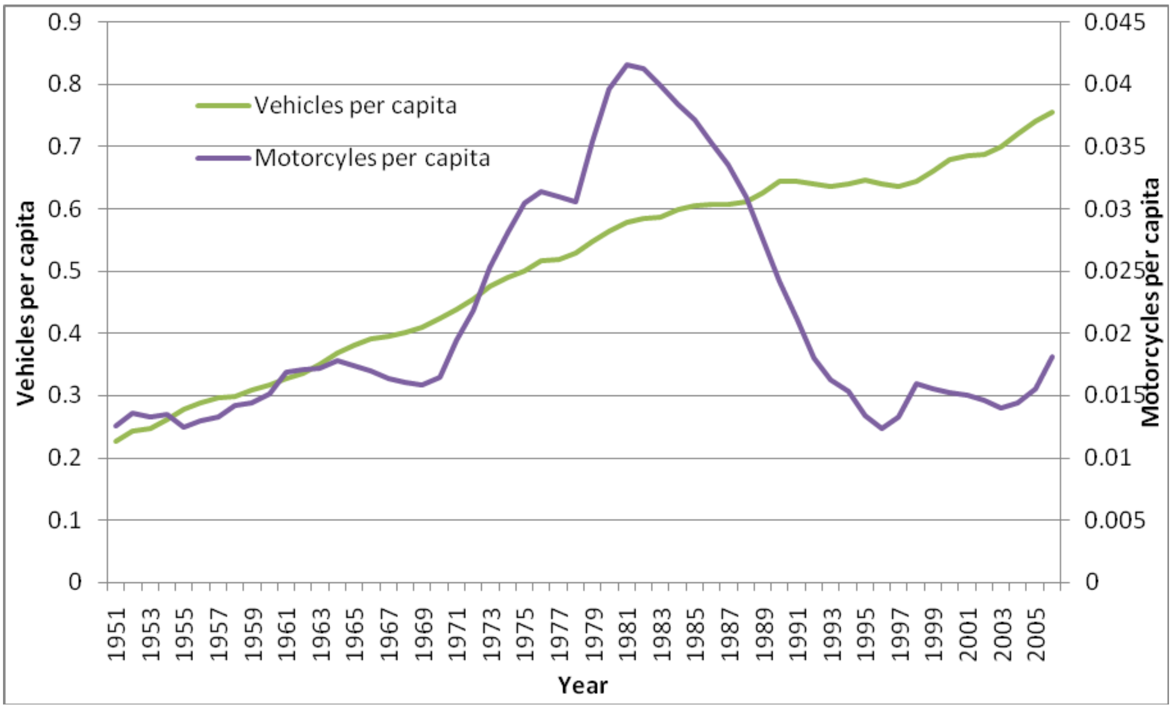
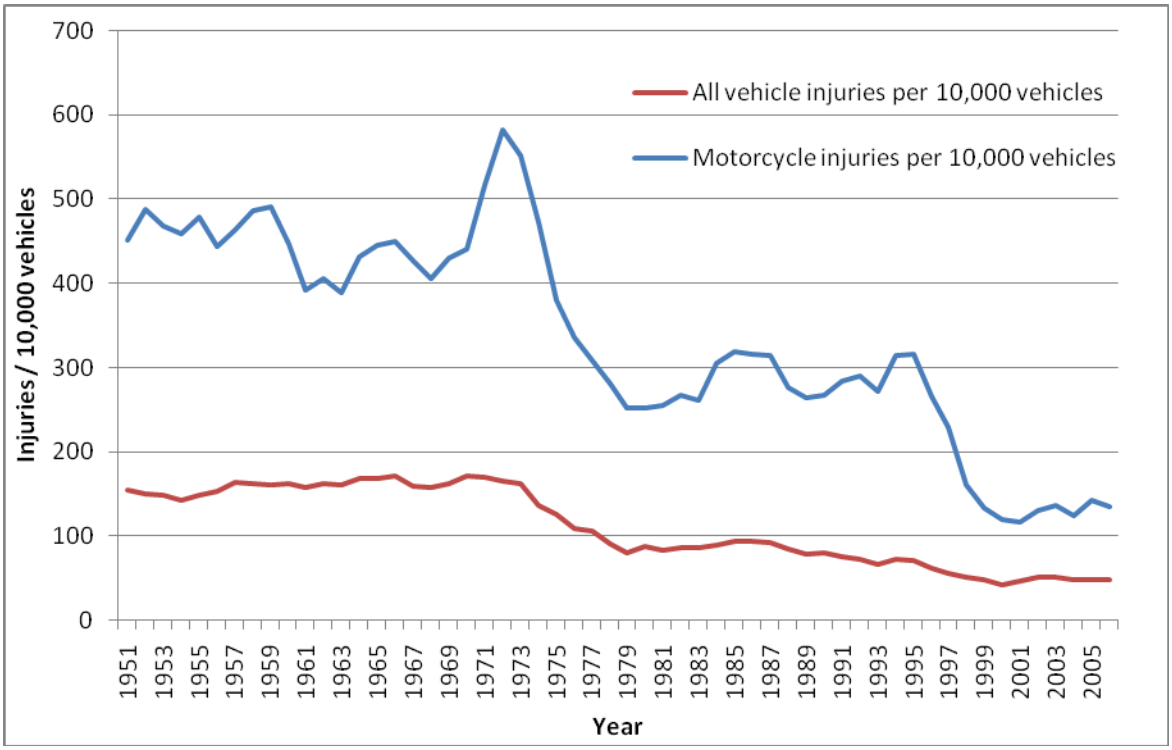
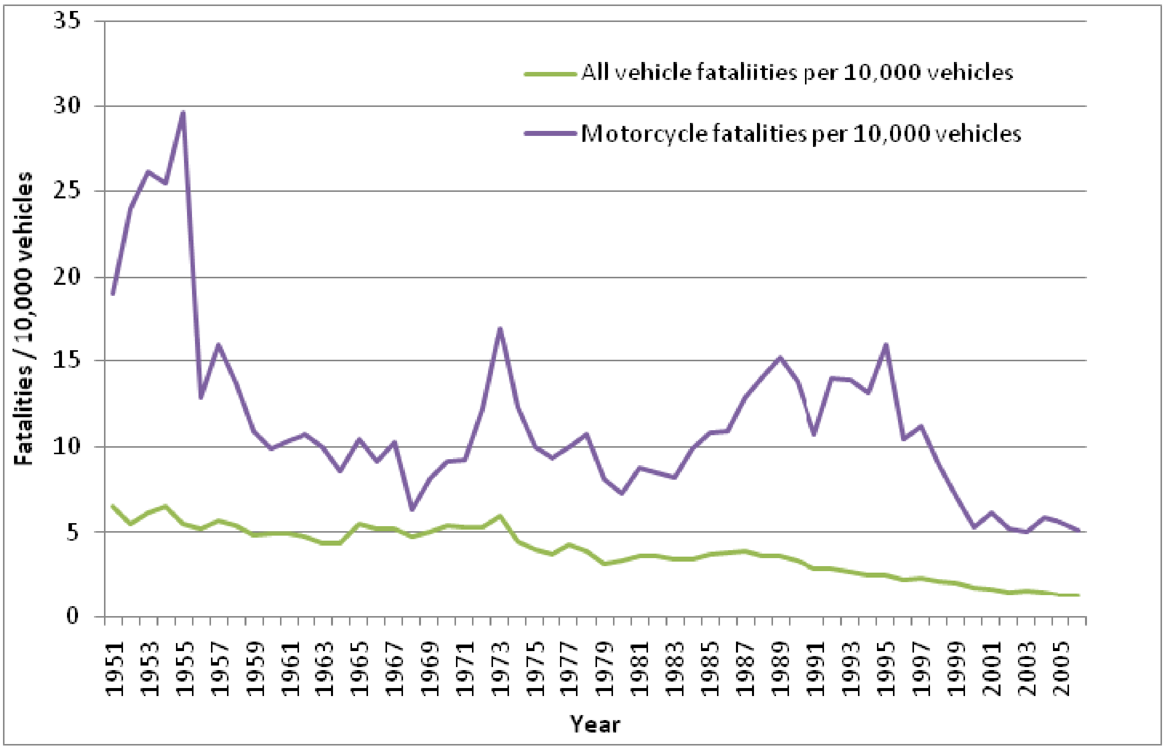


Figure 4.2 Injury rate for motorcycle crashes compared to all vehicle crashes (derived from Ministry of Transport 2008c)



As shown in figures 4.2 and 4.3, the injury and fatality rates for motorcycles are about three times higher than those for all vehicles. In spite of the less-stringent safety requirements for motorcycles, this ratio has remained approximately constant, and the proportional reduction in injuries and fatalities from motorcycle crashes has matched that for all vehicles. In absolute terms, the safety gains for motorcycles have been much higher than those for all vehicles. The interpretation of this data is complicated by the fact that the demographics and use of motorcycles have changed significantly over the 50-year period.

Figure 4.3 Fatality rate for motorcycle crashes compared to all vehicle crashes (derived from Ministry of Transport 2008c)



4.3 Three-wheelers and motortricycles

Various three-wheeled vehicle configurations have existed over the years. Typically, they have been built in relatively small numbers and there have been issues with how they should be treated under the regulations. The New Zealand regulations include a class for three-wheeled vehicles, but many aspects of the rules applying to them are vague or ambiguous.

A common early form of three-wheeled motor vehicle was a motorcycle with sidecar. This is generally treated as a motorcycle under the law. In some jurisdictions, this led to all three-wheeled vehicles being treated as motorcycles, with cheaper registration fees and (at the time) simpler driver licence requirements. As a result, a number of three-wheeled car designs appeared. These had other cost advantages, with either a simplified steering system (with the single wheel at the front) or a simplified drive train (with the single wheel at the rear). On the other hand, the three-wheel configuration, particularly the delta form, has inherent stability problems and is more prone to rollover than a four-wheeled vehicle.

The discussion that follows will be limited to three-wheeled vehicles where the wheels are symmetrically placed about the longitudinal axis of the vehicle. There are two basic configurations used:

- the ‘delta configuration’, which has one wheel at the front and two at the rear
- the ‘tadpole configuration’, which has two wheels at the front and one at the rear.

The delta configuration can be split into two types; one with motorcycle-style controls, and the other with car-style controls. In some jurisdictions, the regulations that apply depend on which type of controls the vehicle is fitted with.

Three-wheeled vehicles span the whole of the automobile era and range from simple, low-technology vehicles to highly sophisticated innovative designs. Figures 4.4–4.11 illustrate the range of vehicles that have been built as three-wheelers. The 1886 Benz Motorwagen shown in figure 4.4 is among the first ICE-powered vehicles ever built. The Aptera Typ-1 shown in figure 4.11 was due to go into production in December 2008, initially to be available as an electric vehicle, with a plug-in hybrid petrol–electric to follow in 2009. The all-electric version was planned to have a battery capacity of 10kWh and to have a range of nearly 200km. The hybrid version, operating on petrol only, was expected to have a fuel economy of 55km/l.

Figure 4.4 1886 Benz Motorwagen (en.wikipedia.org)

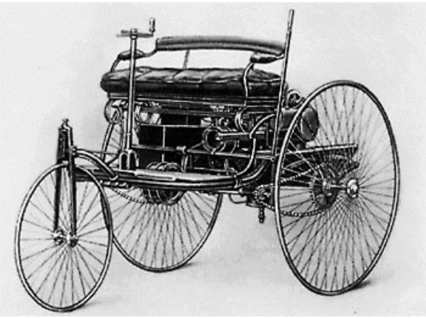


Figure 4.5 1932 Morgan Super Sports Aero (en.wikipedia.org)

Figure4.6 1950s Messerschmitt KR200 (en.wikipedia.org)

Figure 4.7 1999 Reliant Robin (de.wikipedia.org)

Figure 4.8 Modified Harley Davidson trike (commons.wikimedia.org)

Figure 4.9 Sri Lankan tuk-tuk (en.wikipedia.org)

Figure 4.10 2007 Carver One (en.wikipedia.org)

Figure 4.11 2008 prototype Aptera Typ-1 (commons.wikimedia.org)

Three-wheeled cars have generally been small, with relatively small engines. The Morgan shown in figure 4.5 was fitted with an 1100cc air-cooled V-twin engine; the Messerschmitt in figure 4.6 had a 200cc two-stroke single-cylinder engine, and the Reliant Robin in figure 4.7 had an 850cc engine, although earlier models had a 600cc engine. However, these cars were also relatively light, so they performed relatively well, with good fuel economy. The Morgan, weighing about 350kg, was capable of about 130km/h (tuned versions exceeded 160km/h). No official fuel economy figures are available, but there were claims of over 17km/l. The Messerschmitt weighed only 230kg, had a top speed of around 100km/h and a fuel economy of about 28km/l. The Reliant Robin weighed about 450kg, was capable of over 140km/h, and had a claimed fuel economy in excess of 21km/l (some claimed values were as high as 35km/l).

Motorcycle style three-wheelers, such as the Harley Davidson shown in figure 4.8, were typically not as fuel efficient because they were not built as a budget vehicle. The one shown is a motorcycle that was modified by a specialist tricycle builder, as are most of these vehicles. However, the 2009 range from Harley Davidson includes a factory version. The vehicle shown has a 1600cc engine. The motorcycle on which it is based achieved a fuel economy of 14.8/22.8km/l for the US city/highway test cycle. The tricycle would be expected to have a slightly poorer fuel economy because of the extra weight and losses in the rear axle.

The tuk-tuk shown in figure 4.9 is a budget vehicle that is widely used in many parts of Asia. Traditionally, they are powered with small two-stroke engines and do not have a good emissions performance. However, CNG-fuelled versions are now being built and some of these have been imported into Europe for use at tourist venues. These CNG tuk-tuks meet Euro IV emissions standards and thus perform very well.

As noted above, three-wheeled vehicles are less roll-stable than four-wheeled vehicles. The roll-stability improves as the centre of gravity moves closer to the axle with the pair of wheels. Thus under braking, a delta three-wheeler becomes less stable, while a tadpole three-wheeler becomes more stable. This inherent stability problem can be overcome with technology, as illustrated by the Carver One shown in figure 4.10. This vehicle leans into corners like a motorcycle, with the leaning mechanism controlled by computer.

Three-wheelers are generally relatively light, and thus the weight of the driver and passenger can have a significant impact on the handling characteristics. A side-by-side seating configuration means that when there is no passenger, the weight distribution is asymmetric and the vehicle's cornering characteristics differ between left- and right-hand turns – with a right-hand-drive vehicle, stability is enhanced on right-hand curves and degraded on left-hand curves. A tandem seating arrangement overcomes this problem, and has the further advantage that the frontal area can be reduced, resulting in better fuel economy. The optimal aerodynamic shape (for least drag) is a teardrop. This body shape can be approximated most easily with a tadpole three-wheeler with a tandem seating arrangement.

Operationally, the three-wheeler can have some other disadvantages. Because most of the vehicle fleet is four-wheeled, roads with loose material on the surface (snow, gravel and so on) tend to form wheel tracks with a mound of the loose material in between them. The three-wheeler then has its single wheel travelling on the mound of loose material, which can cause steering, and in some cases, traction problems. Many tadpole three-wheelers are driven through the single rear wheel. This can be done very simply using a motorcycle drivetrain, and eliminates the complications and expense of a differential. However, better roll-stability is achieved by having the centre of gravity closer to the front wheels, and thus the drive axle may not be very heavily loaded.

Although there are some three-wheelers, such as the tuk-tuk, being produced in reasonably significant numbers in developing countries, there are very few three-wheelers on the market in the developed world, and government policies and regulations tend to reflect this situation. Broadly, three-wheelers can be classified into those with motorcycle controls and those with car controls. Generally the attitude of the regulatory authorities in New Zealand is that if they are fitted with motorcycle controls, motorcycle regulations apply. That is, the vehicle is not required to meet frontal impact standards, but the rider must wear a motorcycle helmet and must have a motorcycle licence. Alternatively, if the vehicle has car controls, it must have safety belts and meet the relevant frontal impact standards, but the rider does not have to wear a helmet and needs a car driver licence. Although these interpretations seem reasonable, it is difficult to find the details of these specific requirements written in the legislation.

4.4 Four-wheeled cars

In this section we review four-wheeled vehicles that are built within the regulations covering passenger cars; that is, those that comply with all the requirements and are not subject to any specific restrictions or limitations.

There are two broad approaches to achieving better fuel efficiency and lower emissions:

- through smaller lighter vehicles
- through changes in fuel and engine technologies.

The two options are not mutually exclusive, and clearly it is possible to develop smaller vehicles that use some alternative fuel technology. Interestingly, both approaches have been applied quite extensively in the past and, in fact, relatively few of the options being considered at present are genuinely new innovations. With modern technology including new materials, computer control systems and advanced manufacturing techniques, it should be possible to produce much better vehicles using these approaches, and in some cases, overcome the limitations that originally prevented them from being successful.

From the very early days of the automobile, some manufacturers were producing small cars as illustrated by the Morgan three-wheeler shown in figure 4.5. Morgan began producing cars in 1909 and his first model (called a Runabout) had a 7hp motor and, based on the claimed power-to-weight ratio, only weighed about 80kg. The Morgans were three-wheelers and thus do not fit in this category, but other small cars of the 1920s include the Austin Seven, which was enormously successful, with more than 290,000 built between 1922 and 1939. The Austin Seven had a 750cc motor and was available in a range of body styles including four-seater saloon, four-seater open-top tourer, two-seater sports car and a van body. Two examples are shown in figures 4.12 and 4.13. The Austin 7 weighed only 360kg. Official maximum speed and fuel consumption data have not been found, but owner reports indicate a maximum speed of 80km/h and a typical fuel economy of 16km/l.

The success of the Austin Seven resulted in other British car manufacturers producing similar-sized vehicles. Examples include the Morris Minor, which began production in 1929, and the Ford Popular, which began production in 1932. In 1931 the Morris Minor became the first British car to sell for less than £100. A special supercharged model exceeded 100mph (160km/h) on a race track, and in a special fuel-economy trial (without the supercharger and travelling at 24km/h) it travelled 107.4 miles on one gallon of fuel – that is, more than 100mpg (over 35km/l).

In the 1930s, a number of more sophisticated small-vehicle designs were developed, including the Volkswagen Beetle and the Fiat Topolino, which was the first of the Fiat 500s. The Volkswagen was designed as an affordable family car. Although the development was undertaken in the 1930s and a small number of vehicles were produced, full-scale production did not commence until after World War 2, in 1945. These cars had an engine capacity of 1200cc, had a top speed of 115km/h, and a fuel economy of about 13km/l. The Topolino was significantly smaller and more fuel efficient. It had a 570cc engine, a top speed of 85km/h, and a fuel economy of 16.7km/l.

Figure 4.12 1931 Austin Seven four-seater saloon (en.wikipedia.org)

Figure 4.13 930 Austin Seven Ulster two-seater sports car (commons.wikimedia.org)

The period immediately after World War 2 saw a proliferation of small cars being produced in Europe. Several of these have become icons of the era, and were manufactured in large numbers for an extended period. The Volkswagen Beetle remained in production till 2003 and more than 21 million were sold. The Fiat Topolino was produced from 1936 to 1955, with more 500,000 vehicles sold. It was then replaced by the Fiat Nuova 500 (commonly known in New Zealand and Australia as the Bambina or Bambino), which was produced through till 1975. The Bambina has a 500cc engine, weighs 500kg, has a top speed of 85km/h (95km/h on later models), and achieves a fuel economy of about 20km/l.

In France, the Citroen 2CV commenced production in 1949 and continued through to 1990, with more than 5 million vehicles being produced (9 million if all the variants are included). Initially the 2CV had a 375cc engine, although this was increased in stages to 600cc. The 2CV weighs 560kg, and with the latest version of the engine, could achieve a top speed of 110km/h and a fuel economy of about 16.4km/l. To compete with the 2CV, Renault produced the Renault 4. This vehicle was in production from 1961 to 1993 and more than 8 million were produced. Initially the Renault had a 782cc engine, but was upsized to 850cc and then later to 1100cc, and eventually 1300cc. The vehicle originally weighed only 600kg, but was over 700kg with the larger engines. With the 1100cc engine, it had a top speed of 120kmh and fuel economy of up to 16km/l.

The UK also had its iconic small cars, with the Morris Minor (of which about 1.5 million were produced between 1948 and 1971) and the Mini (of which more than 5 million were produced between 1958 and 2000). The original Morris Minor had a 900cc engine, a top speed of just over 100km/h, and could achieve a fuel economy of about 14km/l. Subsequently this engine was replaced with a smaller one (800cc) with more modern design, which in later years was increased in capacity to 950cc, and later, 1100c. The main effect of increasing the engine size was to increase the top speed. Fuel economy remained approximately the same. The Mini was a much more modern car, with front-wheel drive and an innovative suspension system. Initially it had an 850cc engine, but subsequently variants with 1000cc, 1100cc and 1275cc engines were produced. With the 850cc engine, it had a top speed of 120km/h and a fuel economy of about 14km/l. Some of the larger-engine versions were designed for performance and had top speeds approaching 160km/h, with commensurately poorer fuel economy.

As well as these iconic vehicles, many other light, small-engined vehicles were produced in Europe and Japan in the post-war period. These vehicles were primarily a response to the economic situation of the time and provided cheap, economical motoring. A selection of these vehicles is shown in figure 4.14 below. Reliable fuel economy data for these vehicles does not appear to be available, but clearly, with low vehicle weights and small engines, it will have been quite good. The two Japanese examples shown are kei cars (as discussed in section 3.4), which were sold internationally in unrestricted markets and thus are also valid entries in this section. From an emissions perspective, a number of these vehicles used two-stroke motors and thus would not perform satisfactorily by modern standards. Also, the safety requirements of the era were less stringent than those currently in force, and many of these vehicles would be regarded as unsafe today.

Figure 4.14 A selection of light, small-engined vehicles of the 1950s and 60s (www.microcarmuseum.com)

<table>
<tr>
<td>
1951 Atlas Babycar (France)
Engine: 170cc four-stroke
Weight: 270kg
Speed: 60km/h</td>
<td>
1952 Lloyd LS300 (Germany)
Engine: 300cc two-stroke
Weight: 480kg
Speed: 75km/h</td>
<td>
1958 Lloyd LP600 (Germany)
Engine: 600cc four-stroke
Weight: 570kg
Speed: 100km/h</td>
</tr>
<tr>
<td>
1960 BMW Isetta (Germany)
Engine: 300cc four-stroke
Weight: 350kg
Speed: 85km/h</td>
<td>

1958 BMW 600 (Germany)
Engine: 600cc four-stroke
Weight: 515kg
Speed: 100km/h</td>
<td>
1960 NSU Prinz (Germany)
Engine: 600cc four-stroke
Weight: 496kg
Speed: 120km/h</td>
</tr>
</table>

1958 Goggomobil Dart (Australia)
Engine: 240cc two-stroke
Weight: 380kg
Speed: 105km/h

1960 Goggomobil T300(Germany)
Engine: 300cc two-stroke
Weight: 415kg
Speed: 85km/h

1958 Trabant (East Germany)
Engine: 500cc two-stroke
Weight: 560kg
Speed: 90km/h

1964 Lightburn Zeta (Australia)
Engine: 500cc two-stroke
Weight: 400kg
Speed: 125km/h

1970 Subaru 360 (Japan)
Engine: 360cc two-stroke
Weight: 420kg
Speed: 100km/h

1962 Mazda R360 Coupe (Japan)
Engine: 360cc four-stroke
Weight: 380kg
Speed: 90km/h

Although the US also had its iconic vehicles, such as the Ford Model T and others, none of these were particularly light or had small engines. The Model T, which could be regarded as the American ‘people’s car’ (like the Volkswagen Beetle in Germany), was relatively light at 560kg, but had a 2.9l engine and returned a fuel economy of around 5–9 km/l. This performance is not very good, but as the Model T was first built in 1908, this is understandable. The Model T’s replacement, the Model A, was first produced in 1927. It weighed 1027kg, had a 3.3l engine, a reported top speed of 105 km/h, and fuel consumption of 8–12 km/l. These figures can be compared with those of the Austin Seven and the original Morris Minor (given earlier), which were produced in the UK during the same era.

By the early 1960s, the economic situation in most of Europe was improving and car sizes gradually increased. Microcars gradually disappeared from production in most countries, except in Japan where the kei car incentives encouraged their ongoing use, and to some degree, in France with quadricycles, which do not require a driver licence. The gradual increase in car size and engine size is illustrated by the history of the Toyota Corolla, which is summarised in table 4.1. The Toyota Corolla is often listed as the biggest-selling car of all time but, in fact, it has been redesigned a number of times and, apart from the name, the current model has very little in common with the original 1966 model. Although engine technology has improved, the EPA fuel economy figures for the 1985 Corolla (with a 1.6l engine and manual gearbox) are almost exactly the same as those for the 2009 Corolla (with a 1.8l engine and manual gearbox). In the US, the 2009 model has a 2.4l engine option that has poorer fuel economy. Thus, for a Toyota Corolla driver, in over 20 years there has been no significant gain in fuel economy because the improvements in engine efficiency have been offset by increases in engine size and vehicle weight.

Table 4.1 Changing dimensions of Toyota Corollas

Model number	Manufacture years	Weight (kg)	Wheelbase (m)	Engine sizes (l)
E10	1966–70	750	2.286	1.1–1.2
E20	1970–78	770	2.334	1.2–1.4
E30	1974–81	948	2.370	1.2–1.6
E70	1979–83	945	2.400	1.3–1.6
E80	1983–87	1047	2.431	1.3–1.6
E90	1987–92	1086	2.431	1.3–1.6
E100	1993–97	1052	2.464	1.3–1.8
E110	1998–2002	1095	2.464	1.6–1.8
E120	2001–08	1148	2.601	1.8
E140	2006–present	1315	2.601	1.8

The oil price rises of the 1970s prompted some government interventions that aimed to improve the fuel efficiency of the vehicle fleet. There were two contrasting approaches to this issue:

- In Europe and Japan, the regulators used taxes on both vehicle registration and fuel to influence driver choices in vehicle purchase and vehicle use. These taxes included incentives, such as reduced registration fees for preferred vehicles – for example, kei cars in Japan. Subsequently, both Japan and Europe have also set targets for either fuel economy or CO_2 emissions.
- In the US, the government introduced the Corporate Average Fuel Economy (CAFE) regulations in 1975. These required the car manufacturers to achieve specified average fuel targets for the mix of vehicles that they sold. This put the onus on the car manufacturer, rather than the car purchaser. It was expected that manufacturers would use marketing and pricing strategies to increase the sales of smaller, more fuel-efficient cars and reduce the sales of larger, less fuel-efficient cars.

  In practice, the outcome was not so simple. The CAFE standards recognised two vehicle categories – passenger cars and light trucks – and the target fuel economy levels were quite different for the two vehicle types. At the time of the introduction of the CAFE targets, the typical American family car was a large station wagon, which is clearly a passenger car. This vehicle rapidly became obsolete and was replaced by the minivan and the SUV, both of which were classified as light trucks, and thus were not required to be as fuel efficient and did not have to meet the same crashworthiness standards. The 1978 Energy Act imposed a further tax, known as the gas-guzzler tax, on new cars. This was graduated based on fuel consumption rating, and in 2006, ranged from zero for cars with a fuel economy rating of better than 22.5mpg (10.4 l/100km), up to $7,700 for cars with a fuel economy rating of less than 12.5mpg (18.8 l/100km). However, this gas-guzzler tax only applied to cars weighing less than 6,000lb (2,722kg) and did not apply to light trucks (that is, SUVs).

There has been considerable debate on the relative merits of the two taxation approaches (fuel tax or CAFE) and their effectiveness in achieving fuel efficiency. Based on data presented in a report from the Pew Center (An and Sauer 2004), a number of facts are indisputable:

- There have been very substantial improvements in the fuel economy of both American cars and light trucks since the mid-1970s, but since the mid-1980s, the average for the American fleet (cars and light trucks combined) has declined, as shown in figure 4.15. This is a reflection of the increased use of vehicles classed as light trucks (SUVs and so on) as substitutes for passenger cars.

- There have also been substantial reductions in fuel consumption in Europe and Japan, as illustrated in figure 4.16, although for those areas, the starting point (in 1975) was already much lower than in the US.
- The CAFE targets (red traces in figure 4.15) for cars in the US have remained unchanged since 1990, while the light-truck targets were unchanged from 1990 to 2004, after which they were increased. During that period there was a slight decline in the fuel economy performance of the US light-vehicle fleet. Fuel prices were reasonably steady over this period, so in real terms, because of inflation, the price was decreasing (see figure 4.17).
- In Japan, and to a small extent in Europe, there was an increase in average fuel consumption from about 1985 to 1995. Again, fuel prices over this period were stable and thus were reducing in real terms. From 1995 onwards there was again a downward trend in fuel consumption in both Europe and Japan. This timing coincides approximately with the introduction of emissions standards in Europe. Most of these standards are based on grams per kilometre (g/km), so improved fuel economy will generally result in reduced emissions. Japan first introduced emissions standards in the late 1980s, but these remained relatively unchanged until 2005. Thus the fuel economy trend (figure 4.17) does not appear to be aligned to the emissions requirements in Japan. However, in 1993, the Japanese government set fuel efficiency targets to be achieved by 2000. Although these were not legally binding, the nature of the government–industry relationship in Japan is such that industry does regard these targets as mandatory.
- In Europe, the European Community has set targets for the average CO_2 emissions of new cars. Individual member countries develop their own strategies for achieving these targets. In the UK this has been done by implementing a graduated registration fee structure based on CO_2 emissions performance. These targets have been voluntary, and are now being reviewed because the initial targets will not be achieved.

It would appear that both of the approaches have had some significant effect on the fuel efficiency performance of vehicles in the fleet. The effect of the CAFE approach on fleet performance has not been as good as might be desired, for the following two reasons:

1 There is a loophole whereby passenger cars can be substituted by vehicles that are classified as light trucks and thus have a weaker fuel economy target.

2 The target for cars has been static for nearly 20 years. Based on the rapid rate of improvements achieved by the motor industry when the targets were first introduced, and the difference in performance between the US fleet and the European/Japanese fleet, it is clear that further improvements in fuel economy could easily be achieved. In the case of the European/Japanese approach, it is clear that fuel taxes are quite effective, particularly when coupled with government performance targets. However, when fuel prices decline in real terms, this undermines the effect of the fuel taxes.

More recently, concerns about global warming and the contributing effects of GHG emissions have led to a revival in interest in small, fuel-efficient vehicles, particularly in Europe and Japan. Some examples of these are shown in figure 4.18. Most of these cars are bigger than the microcars of the 1950s and 60s, but do achieve fuel economy figures that are at least as good as the older microcars, with the diesel-engined variants being superior. Although these vehicles are relatively light, they are heavy compared to the 1960s microcars. This is largely because they meet modern crashworthiness standards.

Figure 4.15 Trends in US fuel economy 1978–2004 compared to CAFE standards (An and Sauer 2004)

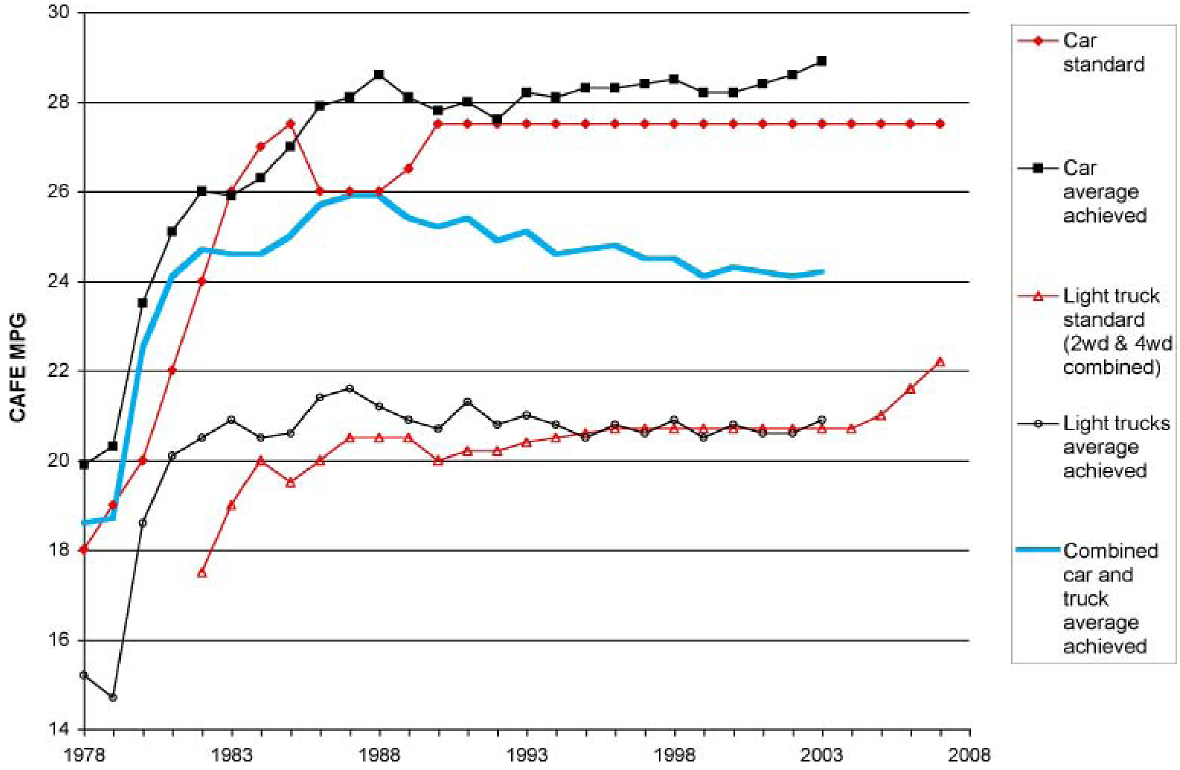


Figure 4.16 Trends in new-car fuel economy (Schipper 2008)

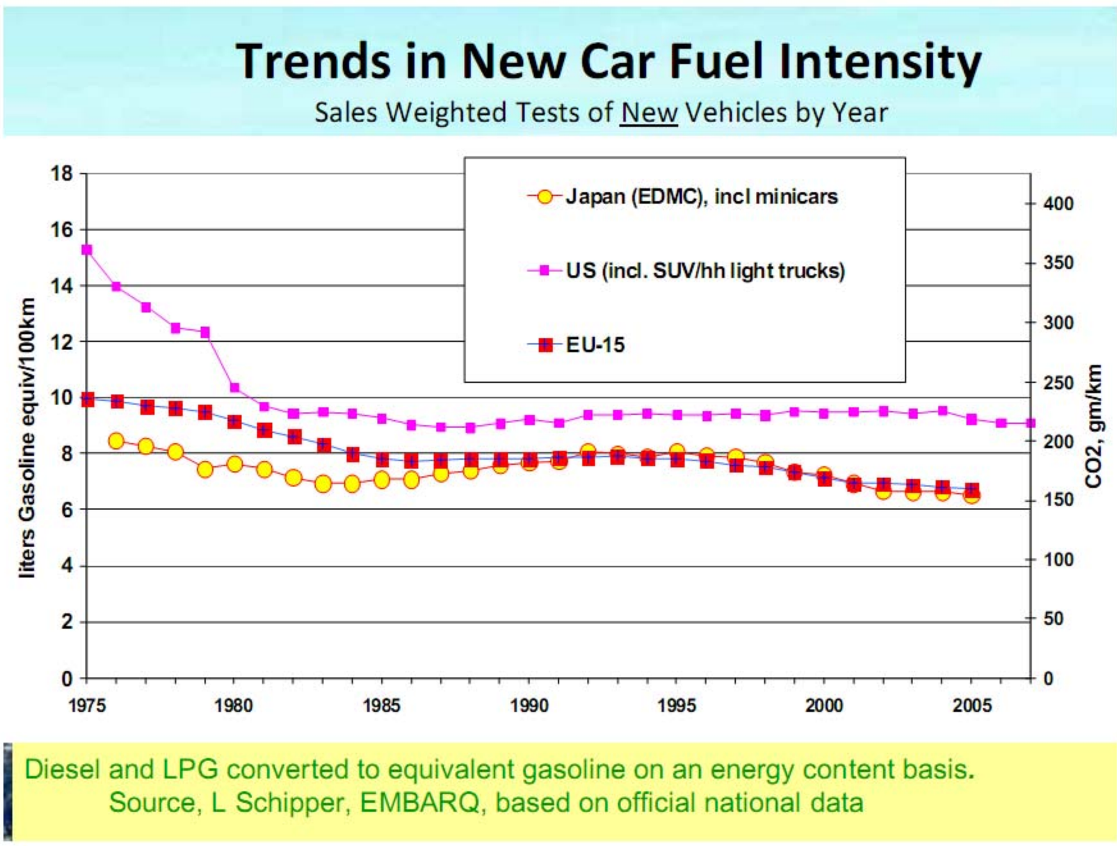
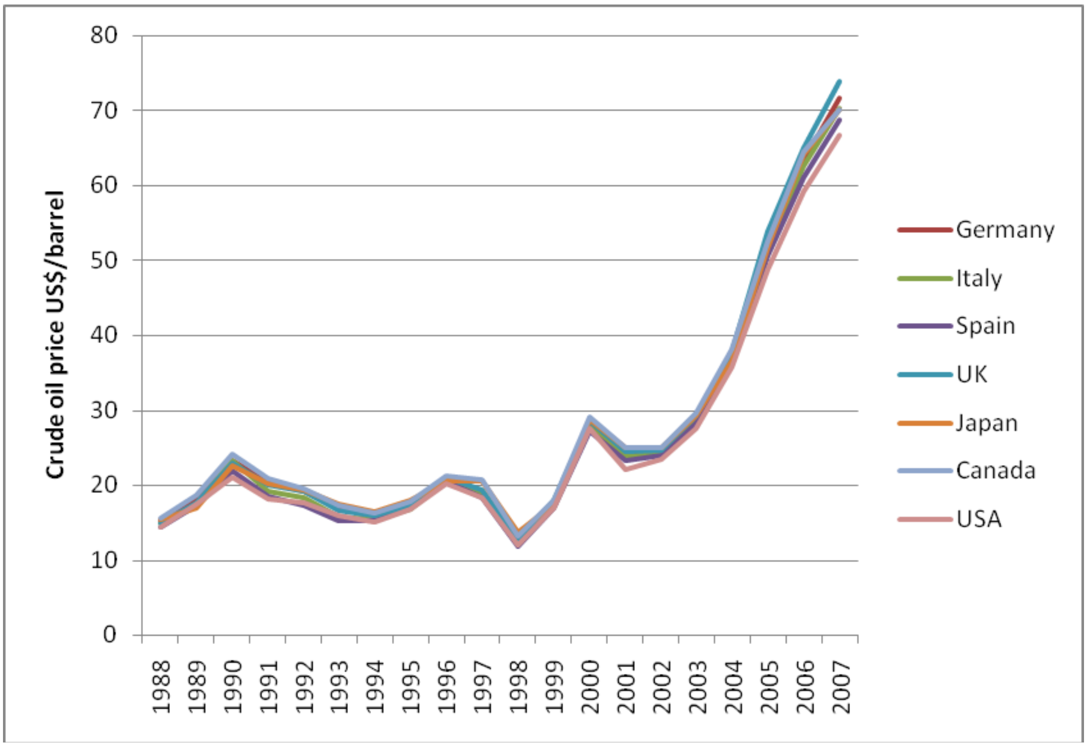


Figure 4.17 Crude oil prices for imports (data from International Energy Agency, OECD 2009)



Some of the vehicles shown in figure 4.18 below are interesting. The Audi A2 (and sister cars by Volkwagen and Seat) achieved extraordinary fuel economy for the 1.2l diesel variant, yet production ceased in 2005, presumably because of lack of demand, and there was no replacement model. The Volkswagen one-litre concept car looks like a modern descendent of the Messerschmitt KR200 shown earlier in figure 4.6 and has the same seating arrangement. In spite of extensive use of modern materials (carbon fibre, magnesium and titanium), it weighs 290kg compared to the Messerschmitt's 230kg. However, it does meet all current safety requirements and is nearly four times as fuel efficient. The Volkswagen Polo BlueMotion is a five-seater city car that has similar fuel consumption to the Messerschmitt.

Figure 4.18 Modern fuel-efficient vehicles (wikipedia.org, www.automobilesreview.com)

Smart Fortwo (1998–present)

Current engine size: 999cc petrol or diesel

Fuel consumption (EU): 4.7l/100km (petrol)
3.4l/100km (diesel)

Toyota iQ (production commencing late 2008)

Engine size: 996cc petrol, diesel to come

Fuel consumption (EU): 4.3l/100km

Audi A2 (1999–2005)

Engine size: 1.4l & 1.6l (petrol),1.2l & 1.4l (diesel)

Fuel consumption (EU): 5.9l/100km (petrol 1.6l)
3.0l/100km (diesel 1.2l)

Toyota Aygo (2005–present)

Engine size: 1.0l (petrol), 1.4l (diesel)

Fuel consumption (EU): 4.6l/100km (petrol)
4.1l/100km (diesel)

Volkswagen Polo Bluemotion (2007–present)

Engine size: 1.4l (diesel)

Fuel consumption (EU): 3.8l/100km

Volkswagen 'one-litre' concept (production–2010?)

Engine size: 300cc (diesel)

Fuel consumption: less than 1l/100km

The discussion above relates primarily to the main currently used fuel technologies; that is, petrol and diesel. We now turn to the potential effect of other fuel and engine technologies that either already exist, or are imminent. A significant number of these technologies date back to the early days of the automobile and were, for various reasons, supplanted in the marketplace by the petrol-driven ICE.

4.4.1 Alternative fuels for use in internal combustion engines

We start with alternative fuels that can be used with conventional engine technologies (that is, ICEs with either spark ignition or compression ignition). Typically, these can be used with current petrol or diesel engines with either no modification or minor modifications.

Biofuels

Currently there are two main biofuels used:

- *ethanol*, which is used as a substitute for petrol
- *biodiesel*, which is used as a substitute for mineral diesel.

It is interesting to note that the first diesel-powered car used vegetable oil as a fuel, and the Ford Model T was designed to run on ethanol – so biofuels are not new.

Biofuels can be used in pure form or blended with petroleum-based fuels. The blending approach is currently the most widely used because most new vehicles can use low-level blended fuels without modification. Typical blends are E10, which consists of 10% ethanol and 90% petrol, and B5, or B20, which consist of 5% or 20% biodiesel and 95% or 80% mineral diesel. The availability of biofuels is somewhat limited, and so using low-level blends that can be used by all vehicles is a good strategy.

In the US, the ethanol is produced from corn. There has been considerable government support for ethanol production for strategic reasons, so supply is stronger particularly in the corn-growing regions. Flex-fuel vehicles have been developed that can cope with any ethanol blend up to E85. In these vehicles, the engine management computer appropriately adjusts the fuel mixture and ignition timing for the fuel. Brazil uses surplus sugar cane to produce fuel ethanol and is the world's largest producer. Many vehicles in Brazil use pure ethanol.

Biofuels are generally cleaner burning than the fossil fuels they replace. The main environmental gain from biofuels is that they are produced from organic materials that extracted carbon from the atmosphere as they grew. Thus the carbon emissions from biofuels are balanced by the carbon extracted from the atmosphere to produce them. However, the complete picture on environmental impacts is more complicated than this. Current biofuels are often referred to as 1st-generation biofuels. In most cases, the crops used as feedstock can also be used as food, and require relatively large areas of what could otherwise be agriculturally (food) productive land. In some cases, rainforests are being converted to palm oil plantations for biodiesel production. Clearly the loss of carbon absorption capacity from the loss of rainforest offsets at least some of the gains from the biodiesel.

A further issue is the amount of energy used to produce and distribute the biofuel. If this energy is in the form of fossil fuels, the net benefit may be negative. Biofuel production in New Zealand is rather limited at present and is largely based around the use of agricultural by-products – milk whey to ethanol, and beef tallow to biodiesel. Second-generation biofuels are under development, and these will overcome many of the issues associated with 1st-generation fuels. These use non-food feedstocks such as wood chips, rubbish, algae and various specialised plant crops that can grow in marginal conditions. The land-use requirements are low, and land that is not suitable for agriculture can often be used.

CNG and LPG

Other fossil fuels can be used with existing engine technologies, although some minor modifications may be needed. The most widely used of these are compressed natural gas (CNG) and liquefied petroleum gas (LPG). These fuels are also relatively clean burning, with low emissions. The use of these fuels has been encouraged in New Zealand and in some European countries through favourable tax treatment. However, the reasons for this are primarily strategic, to promote the substitution of imported petroleum with locally sourced natural gas.

Fuels made from coal or natural gas

There are various processes for making liquid fuels from coal or natural gas; for example, diesel produced using the Fischer-Tropsch process and dimethyl ether (DME), which can both be used in diesel engines. Both Fischer-Tropsch diesel and DME are cleaner burning than mineral diesel, and have lower emissions at the end-use stage. However, we must also consider the emissions generated by the production process, particularly when using coal as a feedstock. Research is being undertaken into methods of capturing and sequestering the carbon released in these production processes. The main driver for using these fuels appears to be finding a substitute for petroleum-based fuels rather than reducing emissions.

Hydrogen

The other alternative fuel that has been widely seen as solution to the problem of reducing emissions is hydrogen. There are two ways in which hydrogen is used as a transport fuel. One is as a substitute fuel in ICEs, while the other is as a feedstock for fuel cells (discussed later with other electric-power options).

As a fuel for ICEs, hydrogen is very attractive. It is very clean burning and emits only water vapour. However, hydrogen needs to be manufactured. The standard method for producing hydrogen is separating it from water, using electrolysis. This requires electricity, and so the emissions associated with using hydrogen depend mainly on how the electricity used in its manufacture was generated.

All of the alternative fuels discussed so far can be used with existing engine technologies, although some modifications may be required. Some of the fuels, such as blended biofuels and Fischer-Tropsch diesel, can be distributed through the existing fuel distribution network. The major issue determining whether these fuels produce overall emission reductions is the level of emissions associated with their production and distribution. Other alternative fuels (CNG, LPG, DME and hydrogen) require their own distribution network and specialised on-vehicle systems for carrying the fuel and delivering it to the engine. Thus, the use of these fuels requires some infrastructure investment. Again, in determining whether they produce an overall emissions reduction, we need to consider the emissions associated with their production and distribution.

4.4.2 Steam cars

Two alternatives to the ICE are steam and electric power. The first 'cars' were, in fact, steam-powered and pre-dated ICE cars by more than 100 years. In the first 30 years or so of automobile history, there were a number of makers of steam cars. Possibly the best-known of these were the Stanley brothers, whose Stanley Rocket set a world land-speed record of 205km/h in 1906.

From an emissions perspective, steam cars have some advantages. They can burn a variety of fuels, and because combustion is external to the engine, it can be much more precisely controlled to give almost perfect combustion with virtually no NO_x, CO or HC (hydrocarbon) emissions. Operationally, steam cars such as the Stanley steamers also had some disadvantages; the main one being that they took a considerable time (typically around 20 minutes from cold) to build up sufficient steam pressure to operate. Although later models were fitted with a condenser, water vapour was lost from the system and thus the vehicles had a 90-litre water tank that needed refilling every 250–400km. This was larger than the fuel tank, which was 76 litres, with a similar range. On the other hand, the steam car had fewer moving parts, required no clutch or gearbox, and was relatively quiet and smooth to operate. Petrol-powered internal combustion vehicles of the same era were hand-cranked to start, which could result in injury.

The development of the electric starter and the much lower price of the mass-produced petrol cars eventually doomed the steam car. The last steam cars of the era were built by the Doble brothers, and these had overcome most of the technical drawbacks of the Stanley vehicles. The Doble could be started from cold in about 30 seconds; water consumption was reduced to the point where the 90-litre water tank would last about 2400km; and it is claimed that the vehicle could meet current Californian emissions requirements. However, the Doble cars were expensive and the business was not well run. Production ceased in 1931. Some examples of Stanley and Doble steam cars are shown in figure 4.19.

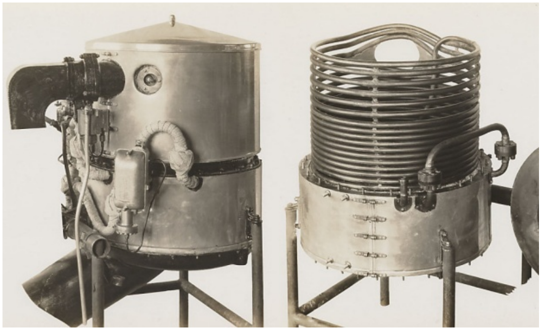
Since the 1970s oil shock, several prototype steam cars have been built, but none have made it into production. Although there would appear to be good potential for a steam car in terms of efficiency and emissions performance, particularly with modern materials and computer controls, there does not appear to be any significant effort by the major automotive manufacturers to develop this technology. It is unlikely that there will be any revival of steam cars in the short to medium term.

Figure 4.19 Examples of steam cars

1918 Stanley Steamer (www.stanleymotorcarriage.com)

Stanley Steamer boiler and condenser (en.wikipedia.org)

1925 Doble E series steam car (www.stanleysteamers.com)



Doble flash boiler (www.damninteresting.net)

4.4.3 Electric cars

Electric cars have also existed since the earliest days of the automobile. The first electric cars were built in the middle of the 19th century; that is, before the first cars with an ICE. Up until the beginning of the 20th century, electric cars held the land-speed record and in the early years of the 20th century, electric cars outsold steam cars, which in turn outsold petrol-powered ICE cars. These early electric cars were very quiet and smooth compared to petrol cars, and had the added advantage that no cranking was required to start them. They were particularly popular with women for urban use, and the marketing targeted these users. Interestingly, the performance of these vehicles was relatively good, even by modern standards. The 1911 Baker shown in figure 4.20, for example, had a top speed of 37km/h and a range of 160km. This compares very favourably with the performance of the modern electric vehicles reviewed in section 3.4. A close look at the figure shows a bouquet of artificial flowers attached to the right-hand door pillar. This is part of the vehicle’s standard equipment and reflects its target market as a woman’s car.

Like steam cars, electric cars were superseded by petrol cars by the 1920s. There were many reasons for this. The advent of the electric starter removed one of the major drawbacks of the ICE. Mass-production techniques, pioneered by Ford, substantially reduced the cost of petrol cars, and thus electric cars were relatively expensive. The perception of the electric car as a woman’s car limited its appeal to male motorists.

Figure 4.20 1911 Baker 'V' extension front coupe (www.conceptcarz.com)

The first hybrid internal combustion–electric cars also date back to the beginning of the 20th century, but only relatively small numbers of these were built. Despite the demise of the electric car, electric vehicles continue to be used for specialist applications, particularly in the UK, where electric-powered milk-floats are used for home milk delivery.

In the 1990s there was a revival of interest in electric vehicles, and several of the major car manufacturers developed models that were eventually produced in relatively small numbers. In some cases, the cars were originally developed by small independent car companies and taken over by the majors. In the US, an important motivation for these developments was California's air-quality regulations, which required manufacturers to sell a minimum number of zero- or low-emission vehicles per year. These regulations were subsequently relaxed and those vehicles were withdrawn from the market.

A selection of these cars is shown in figure 4.21, illustrating the range of designs used. The GM EV1 was a purpose-designed electric vehicle with very low aerodynamic drag and quite good performance characteristics. The Ford Th!nk was originally designed by a small Norwegian company as a purpose-built electric vehicle. This company was taken over by Ford as part of their effort to meet the California zero-emissions vehicle targets. The vehicle was more of a city car that the GM EV1, with lower speed and range capability. After the changes to the Californian regulations and the consequent withdrawal of electric cars from the market, Ford sold its interests in Th!nk. However, the company has continued to operate in Norway and released a new-model Th!nk City that has a slightly higher maximum speed (about 105km/h) and about double the range. The other four vehicles shown in figure 4.21 are all based on similar ICE-powered models, albeit substantially modified to accommodate the electric drivetrain and battery pack.

Figure 4.21 Selection of electric cars of the 1990s

GM EV1 (1996–1999)
Maximum speed: 130km/h
Range: 90–240km, depending on battery type
(jetube.wordpress.com)

Ford Ranger EV (1998–2002)
Maximum speed: 120km/h
Range: 105km+
(en.wikipedia.org)

Ford Th!nk City (1998–2002)
Maximum speed: 90km/h
Range: 85km
(www.aa1car.com)

Toyota RAV4 EV (1997–2003)
Maximum speed: 126km/h
Range: 130–190km
(en.wikipedia.org)

Peugeot 106 Electrique (1998–2004)
Maximum speed: 90km/h
Range: 80km
(www.electroauto.cz)

Citroen Berlingo Electrique (2002–2005)
Maximum speed: 95km/h
Range: 95km
(upload.wikimedia.org)

These vehicles were not usually sold to the general public, but were leased, and often only to corporates and government agencies, rather than to private individuals. When the manufacturers made the decision to withdraw from this market in the US, many of the vehicles were repossessed and destroyed, in spite of the protests of electric-vehicle advocates. Even now, the new Th!nk is sold to purchasers but the battery pack is leased.

The late 1990s saw the arrival on the market of the hybrid electric–ICE car, with the Toyota Prius and the Honda Insight. These vehicles overcome the range limitations of the electric vehicle by adding an ICE. When the power demand is high, such as when accelerating, these vehicles use both sources of power. Thus the ICE does not need to be as powerful to achieve the same performance as a similar vehicle that is powered solely by an ICE. When the power demand is low, the surplus power of the ICE can be used to recharge the batteries. These vehicles incorporate relatively sophisticated control systems and a number of features to improve fuel efficiency, such as regenerative braking, stop–start engine control (the ICE switches off when the power demand is low, such as when idling or crawling in traffic, and restarts itself when the power demand increases), improved aerodynamics and reduced weight. The current Toyota Prius is classified as a mid-sized car in the US and has a fuel economy of 20km/l or 5l/100km, which is not as good as the best of the small cars shown in figure 4.21, although it is a larger car.

This hybrid engine technology has been applied to a number of vehicle models, particularly by Toyota and to a lesser extent, Honda, but also by other car manufacturers in the US. European car manufacturers have tended to favour diesel power as their preferred option for achieving improved fuel efficiency and emissions. Many of the hybrid applications have been to larger vehicles, such as pickup trucks, SUVs and Lexus luxury cars. While these vehicles achieve much better fuel economy than the equivalent petrol-only alternatives, they are not fuel efficient in any absolute sense. For example, the Lexus GS450H hybrid with a 3.5l V6 ICE has comparable power and performance to the petrol-powered GS460, which has a 4.6l V8 engine. The GS460 has a combined fuel economy rating (EPA) of 8.5km/l, while the GS450H has a rating of 9.8km/l. Future directions for hybrids include the use of diesel engines, rather than petrol engines and so-called ‘plug-in’ hybrids. Current hybrid vehicles use the ICE to charge their batteries. The efficiency gains are achieved through smoothing out power demand and recovering energy during braking. Plug-in hybrids charge their batteries from the electricity grid and deplete their batteries when being used. To be effective, they need significantly more battery capacity than current hybrids, but in urban environments they could potentially operate in electric-only mode and thus produce no emissions at all.

Growing international concerns about global warming and GHG emissions have prompted a revival of interest in electric cars in the last few years. Several of the major car manufacturers are about to launch new models. At the same time, a number of small companies have produced new vehicles. A selection of these is shown in figure 4.22.

The Tesla is a high-end sports car that has been under development for a number of years now. After a number of delays, it is now claimed to be in production. It has extraordinarily good performance figures, but is relatively expensive, although not exceptionally so when compared with other high-end sports cars.

As already mentioned, the Th!nk is produced by a Norwegian company that was formerly owned by Ford. Production has commenced, but availability will be limited because the company is quite small. It has been advertised in the UK, which suggests that right-hand-drive models will be available. Currently the vehicle is being sold with the battery pack leased separately. This removes from the owner the risk of problems with the battery pack, and effectively spreads the cost of battery pack replacement over its life, which gives a better indication of true costs, although it increases the apparent running costs.

The Mitsubishi i-MiEV is due to go into production next year, and thus Mitsubishi will be the first large-car manufacturer in recent times to offer an electric car as part of its range. The speed and range figures shown are targets, rather than actual. Thanks to considerable lobbying by Meridian Energy, it is expected that New Zealand will receive some of the first i-MiEVs released onto the market.

The Chevrolet Volt is a plug-in hybrid that is effectively the successor to the GM EV1. However, unlike the Toyota Prius and other hybrids, the ICE does not drive the vehicle. It is only used to charge the batteries when their range is exceeded. The Volt is designed so that 75% of American commuters will be able to do their commuting without using the ICE at all. When the stored charge has been depleted, it is expected to be able to achieve about 20km/l using the ICE.

Figure 4.22 Selection of upcoming electric vehicles

<table>
<tr>
<td>


Tesla (production commenced late 2008)
Maximum speed: 200km/h (limited)
Range: 393km
(www.channel4.com)
</td>
<td>


Th!nk City (production commenced late 2008)
Maximum speed: 105km/h
Range: 180km
(upload.wikimedia.org)
</td>
</tr>
<tr>
<td>


Mitsubishi i-MiEV (production scheduled for 2009)
Maximum speed: 130km/h
Range: 160km
(www.theweeklydriver.com)
</td>
<td>


Chevrolet Volt (production scheduled for 2010)
Maximum speed: 160km/h
Range: 64km without ICE, 20km/l with ICE running
(www.treehugger.com)
</td>
</tr>
</table>

Electric-vehicle performance is still largely limited by battery performance, which affects the vehicle's range and adds weight. New battery technologies have resulted in greater energy density and thus increased range for a given weight. However, these are relatively expensive and add substantially to the cost of the car. For example, the Mitsubishi i-MiEV is expected to cost £12,500 in the UK, whereas the ICE version of the same car costs just over £9,000.

More significantly, the batteries need to be recharged and this is inevitably a relatively slow process. For example, the Mitsubishi i-MiEV has a 16kWh battery pack capacity. With a 240V power supply, this requires 66.7Ah of current without losses. To charge these batteries in, say, three hours, would require a continuous current of more than 22A, which is far more than any household appliance and, in most New Zealand houses, too much for a standard power outlet. Thus, in practical terms, a minimum of a six- to seven-hour recharge time (11A) is needed. The hybrid configuration overcomes this limitation by recharging while driving using the ICE. The downside of this is the complexity, cost and weight of having two power sources on the same vehicle.

An alternative solution is the hydrogen fuel cell. This is often viewed as an alternative engine technology but is, in fact, an alternative battery technology. In a conventional battery, a chemical reaction occurs and generates an electric current. By applying a reverse electric current to the battery, the chemical reaction is reversed and the battery is recharged. In a fuel cell, a chemical reaction occurs that converts hydrogen to water vapour and produces electricity. The usual method of producing hydrogen is by electrolysis, which involves applying an electric current to water to separate the hydrogen and oxygen. This is exactly analogous to recharging a battery. The major advantage the fuel cell has over other existing battery technologies is that the 'recharging' is done outside the battery, and thus it can be done while the battery is in use. The 'recharge', in the form of hydrogen fuel, can be rapidly transferred to the vehicle in the same way as other liquid or gaseous fuels. This flexibility has great appeal, and all of the major automotive manufacturers are researching this technology and many have presented concept vehicles. However, there do not appear to be any fuel cell-driven vehicles that are close to final production.

There have been various incentives supporting electric vehicles in some jurisdictions, particularly in the US (especially California). These have included substantial cash and tax rebates on the purchase price of the vehicle. However, these have not been sufficient to achieve anything more than token sales.

4.5 Light commercial vehicles

Fundamentally, these do not differ significantly from the vehicles of the previous section and, in fact, some of the examples described are commercial vehicles. However, there are some significant differences between some commercial vehicle operations and private car use, which may mean that alternative fuel technologies can be more easily implemented in the commercial fleet than in the private vehicle fleet. Examples of these characteristics are as follows:

- Some light commercial vehicles do much higher annual distances than private cars. Where an alternative fuel/engine technology has higher capital cost but lower operating costs, the payback period for these commercial vehicles will be shorter, and this may make an alternative technology economically sensible, when it is not for vehicles doing a lower annual distance.
- Some commercial vehicles operate out of centralised base facilities. In this case, it may be possible to have refuelling facilities for an alternative fuel at the base(s), enabling the vehicles to use a fuel that does not have an extensive distribution network. This might be a liquid or gas fuel, but could also include exchangeable battery packs for electric vehicles.
- Many light commercial vehicles do not need to have an extended range. Options such as electric vehicles may be viable.
- Vehicle-purchasing decisions are more likely to be based on sound economic analysis by a single decision maker (or a small group). This may work against choosing low-emission vehicle alternatives where they are not economic, but it does simplify the use of incentives.

Internationally, many of the trials of low-emission vehicles have targeted commercial fleets because of these factors – for example, the last two vehicles shown in figure 4.21. Some low-emission commercial vehicles have been used in specialised applications for many years. Perhaps the most notable examples are the electric milk floats that have been used in the UK for over 70 years. These typically have a top speed of 25–30km/h and a range of about 100–130km. An example is shown in figure 4.23.

There has been a substantial decline in the demand for home milk delivery in the UK in recent years and consequently in the demand for milk floats. Several of the major milk float manufacturers have diversified and are now also building small- to medium-sized battery electric delivery vehicles for other applications. These typically have a higher maximum speed and often a greater range. An example is the Smith Edison delivery van (based on a Ford Transit) shown in figure 4.24. This has a maximum speed of about 80km/h and a range of about 160km. However, it also costs over $120,000, compared to just over $40,000 for a similar diesel-powered vehicle. It is claimed that the maintenance costs of the electric version are significantly lower because the drivetrain is much simpler and there are fewer moving parts. Nevertheless, at current diesel prices in New Zealand, it is difficult to see any economic advantage for the electric version. Current (April 2009) prices for diesel in the UK are around NZ$2.50/l. In addition, the electric version is exempt from road tax and from the London congestion charge. Thus, in some UK operating environments, the electric version could have a lower whole-of-life cost.

Figure 4.23 UK electric milk float (en.wikipedia.org)

Figure 4.24 Smith Edison electric delivery van (www.greencarsite.co.uk

)

5 Fuel and engine technologies

5.1 Introduction

The discussion so far has reviewed the different types of vehicles that are either available at present or on the near horizon. This analysis has identified various fuel and engine technology options. This section summarises the key characteristics of these options in terms of the state of the technology, their potential range of application and limitations, and their emissions performance.

One of the complications of this review of fuel and engine technologies is that hybrid vehicles, by definition, use more than one fuel and engine technology. To overcome this we consider the ‘pure’ technologies first, and then the hybrids. That way we can refer back to the previous discussion when reviewing the components of the hybrid system.

5.2 Human power

Human power has an excellent emissions performance. The human engine does consume additional food to create the power and thus will produce more CO_2 – but because that food will have been produced from biomass, the CO_2 was previously extracted from the atmosphere, and so the net emissions will be zero. Templeton (2008) argues that the fossil fuel used in food production (which in the US is very high) should be included. However, New Zealand agriculture is much less energy intensive than in the US, and we will ignore this effect.

The technology behind basic human-powered vehicles, such as bicycles, is very simple and has a relatively low emissions impact. Most bicycles are made from various metals, which consume energy in their production and thus produce some emissions. However, to be effective, a bicycle must be light and so the quantities involved are very small. Some of the modern developments (such as the HPVs described in section 2.3) use more exotic materials such as carbon fibre composites, which use fossil fuels in their production – but again, the quantities are very small compared to other vehicles.

The main limitation on human power is that the maximum amount available per person is relatively small. This limits the maximum speed achievable by a human-powered vehicle and effectively, the practical range, because of the time needed. It also limits the load-carrying capacity. For relatively short journeys and modest loads, there is no better option than human-powered vehicles for fuel efficiency or emissions.

Technological developments, in the form of more efficient vehicles, will lead to some increase in maximum speed and hence usable range. However, one cannot get more power out than one puts in, and thus the maximum power limitation cannot be overcome.

5.3 Electric drive

Although battery electric cars were first built more than 100 years ago and there has been a substantial investment in the development of modern electric cars over the last 20 years or more, progress in the state of electric-vehicle technology has been modest. Although the modern electric car has a much higher maximum speed than the vehicle of 100 years ago, its range is similar.

The key to electric-vehicle technology is the storage of electric power, and there are three technologies being developed for this function; batteries, fuel cells, and supercapacitors or ultracapacitors. Although batteries and fuel cells are generally perceived as quite different technologies, they are fundamentally very similar, as explained in the previous section. In both cases, a chemical reaction occurs, which generates an electric current. In the case of (rechargeable) batteries, this is reversible and thus applying a reverse electric current causes the chemical reaction to be reversed. With a fuel cell, hydrogen and oxygen react to form water, which is released rather than contained. However, applying an electric current to water produces the reverse of this reaction and generates hydrogen and oxygen, which can be fed into the fuel cell to again produce electricity. Thus, effectively the recharging of the fuel cell is done off-line.

This has both advantages and disadvantages. The main advantage is that the vehicle does not have to be taken out of service during recharging. Hydrogen can be supplied to the vehicle like a fuel (oxygen could also be supplied, but normally this is extracted from the air as needed) and thus the vehicle can operate effectively on a continuous basis. The disadvantage of using fuel cell technology is that no on-line recharging is possible, and thus it is not possible to recover excess energy through regenerative braking. Generally this problem is overcome by also having battery or supercapacitor storage on the vehicle, although there is a fuel cell technology (a unitised regenerative fuel cell) that can operate in reverse and thus absorb energy and produce hydrogen, which can be stored and subsequently reused.

The three electric storage methods each have advantages and disadvantages, and it may be that in the longer term, electric vehicles will use all three. Currently, battery-based storage systems are the only ones in commercial use on electric vehicles.

5.3.1 Batteries

Various battery technologies are used and there is a price/performance trade-off. Lead-acid batteries are at the bottom of the range. These have been widely used in automotive applications for many years. They are relatively heavy, with energy densities of about 30–40Wh/kg; they have moderate durability, with a life of about 500–800 charging cycles; and they are relatively cheap (NZ retail prices typically $0.26–$0.56/Wh). Modern electric vehicles have used nickel cadmium (Ni-Cd), nickel metal hydride (NiMH), and lithium-ion batteries, among others. Lithium-ion appears to be the currently favoured option for higher-specification vehicles, although it should be noted that the term lithium-ion refers to a family of battery technologies. These have the best energy density currently available, at 100–160Wh/kg; they have a greater durability than lead-acid, with a life of about 1200 charging cycles, although this greatly affected by how well the charging is managed; and they are much more expensive, retailing for about $1.40/Wh in New Zealand.

To illustrate the effect of the price/performance difference between lead-acid and lithium-ion batteries, we can compare two current models of the Reva G-Wiz (see section 3.4 and figure 3.7). The only significant difference between the two models is that one has a lead-acid battery pack and the other has a lithium-ion (Li-ion) pack. The lead-acid battery pack contains 9.6kWh of energy and gives the vehicle a range of about 80km. A replacement battery pack costs about UK£1600 (NZ$4000). The vehicle with the Li-ion battery pack weighs 100kg less and has a range of about 120km. This vehicle costs UK£7,800 (nearly NZ$20,000) more than the vehicle with the lead-acid batteries. We have not been able to find data on the capacity of the Li-ion battery pack, but based on the range, it is likely to be no more than about 14kWh. The lead-acid battery pack has an expected life of about two to three years of normal use, while the Li-ion batteries are guaranteed for three years and hence are likely to last at least four to five years on average.

Although the running costs of these vehicles are very low, compared to conventional petrol or diesel cars, the high cost and relatively short life of the battery pack means that this must be included in any assessment. This also applies to the assessment of emissions performance.

Considerable research effort is being applied to improving the performance of batteries, and there are a number of developments which, if they realise their claimed potential, will have a dramatic impact on the acceptability of electric vehicles. For example:

- The Altairnano batteries are Li-ion with an innovative anode design. These are claimed to have three times the power intensity of conventional Li-ion batteries and significantly increased durability (more than 5000 charging cycles). It is claimed that they can be fully recharged in 10 minutes. The downside is that the energy intensity, at 74Wh/kg, is significantly lower than the best Li-ion (100–160Wh/kg). These batteries are currently being supplied to an electric car manufacturer (Phoenix).
- Recent research (Chan et al 2008) showed that Li-ion batteries using silicon nanowire anodes can achieve energy densities up to 10 times that of conventional Li-ion batteries. This technology has been patented, but has not yet been commercialised.

5.3.2 Fuel cells

Fuel cell-based vehicles have been built and operated as prototypes, but are not yet commercially available. Honda has one model, the FCX Clarity, which is currently being trialled in Southern California. They hope to have 200 of these on the road over three years (the first one was delivered on 25 July 2008). These are being offered on a leased basis for US$600 per month (Honda 2009b). The FCX Clarity has comparable engine performance to a Honda Civic, but is physically more similar in size to a Honda Accord. The lease cost for Honda Civics and Accords ranges from less than US$300 per month up to US$490 per month, depending on specifications (Honda 2009a). Currently, fuel cell vehicles are expensive and, more critically, their use is limited by the lack of a hydrogen distribution network. There are also technical issues relating to the on-vehicle storage of hydrogen that need to be addressed. One of the alternative approaches is to use a hydrocarbon or alcohol fuel (methanol, ethanol, methane, or even petrol) and a reformer, which extracts the hydrogen from this fuel. The advantage of this approach is that these fuels are much easier to handle than hydrogen. The disadvantage is that the reformer produces carbon dioxide and so we no longer have a zero-emissions vehicle. Most of the major car manufacturers are working on fuel cell vehicles, and clearly they see them as an important future technology direction.

5.3.3 Supercapacitors

Supercapacitors, also known as ultracapacitors, store electricity by a physical process rather than a chemical process. They have some advantages over batteries in that they have a much higher power density. This means that they will tolerate much higher charging and discharging rates. This offers the potential for very short recharge times (minutes rather than hours) and is a useful characteristic for providing high power boosts during acceleration, and for providing high regenerative braking forces when needed. They can also withstand many more charging cycles than batteries, and would be expected to outlast the vehicle.

However, the energy density of commercially available supercapacitors is around 6kWh/kg, which is significantly less than even lead-acid batteries. Research by Kassakian et al (2006) postulated that supercapacitors based on carbon nanotubes could achieve energy densities in excess of 60kWh/kg. Although this is only about half the energy density achieved by Li-ion battery systems, the capability for very rapid recharging and the long life (in terms of charging cycles) would make these supercapacitors a strong potential candidate as the future storage medium for electric vehicles.

A company called EEStor claims to have developed the technology to overcome many of the limitations of ultracapacitors. Their EESU (electrical energy storage units) are claimed to have a capacity of 52kWh, weigh 181kg (400lb), be able to be charged in minutes rather than hours, and will initially have a selling price of US$3200, reducing to US$2100 with volume production (Fraser 2006). If these performance parameters are achieved, it will revolutionise electric vehicles. This energy density (287Wh/kg) is more than double the best achieved by current Li-ion batteries, the projected cost (US$0.06/Wh) is lower than lead-acid batteries, and this is combined with the potential for fast recharging. EEStor has a number of patents on the technology and has entered into a partnership with an electric-vehicle manufacturer (Zenn) but, at the time of writing, no EESU had been independently tested or publicly demonstrated.

5.3.4 Barriers

Currently, the main barriers to greater uptake of electric vehicles are cost and perceptions of performance, particularly relating to range. At the small-vehicle end of the range, these barriers are not great. For example, electric mopeds are not significantly more expensive than the petrol-powered alternatives. It is difficult to do an accurate comparison because we have not been able to find two vehicles that are identical in all other respects. The range of these smaller vehicles is quite limited, but these are low-speed vehicles designed for commuting and they are not expected to be used for long trips.

However, for car-sized vehicles, these barriers are significant. The Mitsubishi i-MiEV is due for release this year and some demonstration vehicles have been operating in New Zealand. Various commentators (Anon 2008, Fung 2009) reported than the initial selling price in Japan is ¥4M (NZ$69,500) although Japanese buyers are expected to get tax credits of ¥1M, so the final cost to the consumer is ¥3M (NZ$52,000). Thus, it is expected than this vehicle will retail in this country for around NZ$60,000. No pricing has been given on the battery pack, but given its size, it is likely to cost somewhere around NZ$20,000–$25,000. This electric vehicle is based on the same platform as the Mitsubishi i-car, which sells for NZ$19,000. The i-car has a 660cc engine and a rated fuel consumption of 5.9l/100km. If we assume that this vehicle will travel 250,000km in its life, its total fuel consumption will be less than 15,000l. At current fuel prices, this is less than NZ$24,000. Thus the cost of the petrol car, and all the petrol it uses in it whole life, is significantly less than the expected purchase price of the electric car. Based on the quoted range of the electric car, the battery pack would need to undergo more than 1500 charges in a 250,000km life. This is more than the expected life of current Li-ion batteries, so it is likely that the battery pack would need replacing. Clearly, the electric option is not a sound economic choice.

The other barrier is range and as noted above, this is largely, although not entirely, an issue of perception. Numerous commentators in many countries have pointed out that the vast majority (95% or more) of car journeys are within the range of modern electric vehicles. However, a comparable ICE vehicle typically has a much greater range on a tank of fuel, and because it can refuel in a matter of a few minutes, it effectively has an infinite range. This fast refuelling capability also means that users do not have to plan their travel around the vehicle’s range at all. Electric vehicles do not currently have this flexibility.

Fuel cells clearly have the potential to match this performance characteristic of ICE cars, but a fuel distribution network would have to be established. In the short to medium term, batteries and supercapacitors are unlikely to achieve the same range per charge as ICE vehicles, but there are developments that suggest that rapid recharging will soon be possible. The distribution network for electricity already exists. For rapid charging, specialised outlet facilities will be required and there are potentially some safety issues. To charge a 16kWh battery pack (the size of that in the Mitsubishi i-MiEV) in 10 minutes from a 240V supply would require a current in excess of 400A. This is a high-power (96kW) feed and far exceeds the capacity of the usual domestic power supply, and probably that of typical service stations. However, it would be feasible to have a bank of supercapacitors charging continuously at a lower rate, and then to use these to charge the vehicle systems. Slower plug-in charging facilities could be provided in car parks, shopping centres, and so on.

A more sophisticated inductive charging system has been developed by the Power Electronics Research Group at Auckland University. This does not require any physical connection between the transmitter and receiver. Furthermore, the transmitter can be buried beneath the pavement so there is no visual pollution.

They claim that existing versions of their system have power transfer capabilities up to 200kW, which is sufficient for fast charging. This system does require the vehicle to be fitted with the appropriate receiver.

Concepts such as exchangeable battery packs have been proposed as alternatives to fast charging. To be viable, standardisation of batteries and a pricing system that incorporates the reduction in battery-pack life would be required. This may be a useful system for commercial fleets, but it would appear to be difficult to implement for privately owned vehicles. It has also been suggested that EV battery packs could be used to provide storage for the electricity grid and thus be used for smoothing the demand peaks. However, at current battery prices, this would require the grid to pay a substantial premium for the power it draws from the vehicle batteries. If the cost of a Li-ion battery is NZ$1,400/kWh and the battery pack has a life of 1200 charging cycles, the owner of the batteries would need to recover at least NZ$1.17/kWh for the loss in battery life, over and above the cost of the power, which currently averages about $0.21/kWh in New Zealand.

5.4 Steam engines

As noted in section 4.4, the first cars were powered by steam. Steam engines are a form of external combustion engine. This has some significant advantages in terms of emissions. The combustion takes place in much more easily controlled conditions and thus it is much easier to achieve optimal performance. As well, a much wider range of fuels can be used and fuel quality is not so critical. Steam engines also have some driveability advantages. The steam engine produces maximum torque at zero engine speed. Thus there is no need for a transmission or a clutch and initial acceleration is strong. Furthermore, the engine operates at a relatively low engine speed (typically up to about 900rpm) and so it is relatively quiet, compared to ICEs. However, there are also some disadvantages. Traditionally, steam engines have had relatively long start-up times, particularly in cold weather. Steam is lost from the system and must be replenished. This requires carrying quantities of water and having to stop to refill the water system regularly. By the 1930s these disadvantages had been largely overcome, but by then, ICE-powered vehicles were in mass production and were significantly cheaper than steam cars, which were only being produced by a very small number of boutique manufacturers.

The potential efficiency of a steam engine depends on the temperature of the steam that is used. With modern materials (ceramics and so on) and modern control systems, it should be possible to build a steam-engine vehicle that has a good emissions performance and good driveability. There have been some attempts to do this. Responding to the 1973 oil crisis, Saab, in 1974, initiated a research programme to develop a new steam engine (Platell 1976; Ryan 2008). The initial results were promising and there was speculation that Saab intended to apply the technology to its production cars in the future. However, the project appears to have been shelved.

In 1996 Enginion AG, a subsidiary of Volkswagen, began developing a modern, efficient steam engine with a view to automotive applications. The company subsequently became part of IAV GmbH, a large independent automotive research and development company. The engine was compact, fuel efficient, and produced very low emissions (Buschmann et al 2001; Mößbauer et al 2001; Sawyer 2001). The developers subsequently decided to focus on the stationary-engine market and small-scale power generation. This application has efficiency advantages, because the waste heat from the engine can also be used. The subsidiary company developing the engine is now called TEA GmbH and is still listed on IAV website, but there is no new information on technical progress or potential commercialisation.

Steam engines appear to have reasonably good potential for low emissions. It is likely that fuel consumption rates similar to those of diesel ICEs could be achieved. External combustion is much easier to control, and it is easier to meet air-quality emission standards without complicated exhaust treatments.

Furthermore, they can accommodate a wide range of fuels relatively easily. Nevertheless there seems to be very limited research and development activity on this technology by the large automobile manufacturers, and a major revival of steam-powered vehicles is very unlikely.

5.5 Compressed air drive

This technology has attracted some attention in recent years. This is mainly due to the activities of a Luxembourg company called Moteur Development International (MDI) and its CEO, Guy Negre (Anon 2009). MDI was established in 1991. Its website shows five different vehicles, with detailed specifications (including pricing) for each of them. Prototypes have been built and shown at international motor shows since at least 2000, with press releases indicating that production was imminent (Dempster 2000). The company signed an agreement with Tata Motors of India in 2007, and publicity releases indicated that 6000 vehicles would be built in 2008 (Sullivan 2007). At the time of writing, no commercial vehicle had been built.

A quick analysis of the published vehicle specifications suggest that some of the claims made for these vehicles are very optimistic. The claimed ranges are about double those achieved by comparably sized electric vehicles. Yet even with the lightest tank technologies (wound carbon fibre) operating at 350bar, compressed air has an energy density similar to that of lead-acid batteries. The air itself without the tanks has an energy density of 135Wh/kg, which is similar to that of Li-ion batteries. These energy calculations are isothermic and do not take into account the heat losses that occur when the gas expands. If the air engine could achieve the same efficiency as an electric motor, which is unlikely, the range would be expected to be comparable with electric vehicles using lead-acid batteries.

It is interesting to note that in the first trial of a prototype MDI taxi that was undertaken at Brignoles in France in 1998, the vehicle achieved 7.22km on its full charge of air, compared to the 200km range claimed. This prototype was significantly heavier than the proposed final design, had steel air tanks with a pressure of 200bar (rather than the 300bar carbon tanks proposed for the final design), and was missing a number of other features, which the company claimed accounted for the difference. At the time of the 1998 trial, the company also claimed they would be in production by 2000.

The vehicles have an electric on-board compressor, and thus can be refuelled by plugging them in. Alternatively, they can be refuelled very rapidly from a compressed-air supply. The existing compressed-air supplies at service stations do not operate at sufficient pressure for this function, but it would be relatively simple to provide this facility if the demand existed.

Indranet Technologies Ltd has formed a joint venture company, IT MDI-Energy Ltd, to market MDI vehicles in New Zealand and Australia. A press release dated 9 October 2008 indicated that they would be showcasing some of the technologies in New Zealand and Australia later in 2008 and early in 2009. As far as we know, this has not yet occurred.

5.6 Internal combustion engines

5.6.1 Introduction

The most widely used technology for powering transport vehicles is the internal combustion engine (ICE), which has two basic forms: spark ignition (SI) or compression ignition (CI). The most common SI engine is petrol fuelled, while the most common CI engine is diesel fuelled. For most of the history of the motor vehicle, petrol-powered SI engines have dominated the light-vehicle fleet. Diesel-fuelled CI engines have tended to be heavier, noisier and lower revving, but producing higher levels of torque and better fuel economy. They have been used primarily for heavy vehicles.

Since the oil crisis of the 1970s there has been a revival in interest in the use of diesel-powered light vehicles, and considerable effort has been applied to improving their performance. Currently, the modern diesel-powered light vehicle has comparable performance with its petrol-powered equivalent. The diesel-powered vehicle is more fuel efficient, and thus produces fewer GHG emissions. However, it is not as clean burning and has poorer performance with respect to air-quality-related emissions. The current emissions standards make some allowance for these differences.

For both engine types, there have been considerable advances in fuel efficiency in recent years, although this has only partially translated into fleet performance because there has been a trend for consumers to purchase larger-engined vehicles.

Various alternative fuels have been developed, which can be used in either an SI or CI engine with a greater or lesser degree of modification required. In this section we review the main alternative fuel options.

5.6.2 Biofuels

Biofuels are derived from biomass. Their use as a fuel goes back to the very beginnings of the motor vehicle, when petroleum-based fuels were expensive and difficult to obtain. The first diesel engine ran on peanut oil, and the original Model T Ford was designed to run on ethanol, or petrol, or blends. The oil shocks of the 1970s rekindled interest in biofuels, and since that time they have been used in a number of countries, usually in the form of blends with petroleum fuels.

There are two main forms of biofuel in use today: ethanol and biodiesel. Ethanol is usually blended with petrol and is used in SI engines, while biodiesel is usually blended with mineral diesel and used in CI engines. In both cases, it is possible to use the fuels in pure form without blending at all. The blended fuels are referred to with a letter code followed by a number representing the percentage of biofuel in the blend. Thus E10 is petrol blended with 10% ethanol, and B5 is diesel blended with 5% biodiesel.

Internationally, the leading country in the use of biofuels has been Brazil, where surplus sugar cane has been used to make ethanol for fuel since the 1920s. In 1975 the Brazilian government introduced a 'Proalcool' programme, with the aims of using high (15% or more) ethanol blends and incentivising the development of 100% ethanol vehicles (Joseph 2009). Initially, the government provided incentives and subsidies and there was a strong uptake of the technology. In 1987 the government removed the subsidies, and the combined effect of high sugar prices and cheap oil led to a decline in ethanol use, and particularly in the sale of E100 vehicles. From 1999 onwards, the price of ethanol in Brazil has stabilised at about 50% of the price of petrol. In 2003, vehicle manufacturers introduced flex-fuel vehicles that can operate on any ethanol blend, from 0%–100%. Currently, about 85% of new-car sales in Brazil are flex-fuel vehicles; about 10% are E22 capable; and the remainder are diesel (Joseph 2009). Jeuland et al (2004) reported that 20% of the Brazilian vehicle fleet operate on E100, with the remainder using E22. Because of the rapid increase in flex-fuel vehicle sales since 2004, the proportion of vehicles using E100 will now be significantly higher. The Ethanol Fact Book (Anon 2007a) reports that ethanol now accounts for 40% of Brazilian automobile fuel.

The US has also been a major adopter of ethanol use, although at a significantly lower level than in Brazil. Ethanol in the US has been produced primarily from corn. The use of ethanol in the US was also a response to the oil crisis of 1973, and was initiated by the Energy Tax Act of 1978, which exempted E10 fuel from the federal fuel excise tax (Anon 2007a). Since that time, various other government initiatives have been enacted to support the use of ethanol as fuel, including incentives to manufacture flex-fuel vehicles that can handle any ethanol blend, from zero to E85. All the major car manufacturers now offer these vehicles without any price premium, and there are more than six million of them operating on American roads

(Anon 2007a). In spite of relatively high levels of uptake (in some of the corn-belt states, all petrol contains ethanol), the amount of petrol replaced by ethanol is still modest. The Ethanol Fact Book (Anon 2007a) notes that in 2005, American motorists consumed 534 billion litres (141 billion gallons) of petrol. In 2007, they estimated that 26.5 billion litres (seven billion gallons) of ethanol was produced, and that they expected production capacity to rise to nearly 38 billion litres (10 billion gallons) in 2008. Even at this highest value, ethanol was only replacing less than 7% of petrol consumption.

Europe has been slower to act on promoting biofuels, but has recently introduced a number of measures. The 1999 European standard for petrol, EN 228, allows for petrol blends of up to 5% ethanol to be sold without labelling. In 2003, the European Parliament and council issued a directive, 2003/30/EC, on the promotion of the use of biofuels, or other renewable fuels, for transport. The aim of this directive was for the percentage of fuel energy being derived from biofuel in EC member countries to be 2% by 2005, and 5.75% by 2010. Thus the use of biofuels is expected to increase substantially. The 2005 UK report to the EC on progress towards the aims of the directive detailed tax incentives introduced in early 2005, and noted a substantial growth in the use of ethanol blends (mainly E5) using imported Brazilian ethanol. Although the growth had been substantial, the overall level of E5 use was still small.

In 2008, the New Zealand government introduced a biofuels sales obligation that required the oil companies, over time, to achieve target levels of biofuels in their petrol and diesel sales. Following the change of government in late 2008, this requirement was repealed. At the time of writing, one of the smaller oil supply companies was offering E10 at its service stations, but the large oil companies were not.

There are differences between the properties of ethanol and petrol that have the potential to cause compatibility problems for some engines. The car manufacturers tend to take a conservative attitude towards these potential problems. It is widely accepted that all vehicles can cope with E3 with no ill effects. All European-sourced cars since 1998 should be able to cope with E5, because it could have been supplied to them without labelling. All American cars manufactured since the late 1970s can cope with E10, and all Japanese cars produced for the New Zealand market since 2005 are E10-compatible, although second-hand imports are not necessarily rated as compatible. There are lists of makes and models that have been endorsed by the manufacturer as E10-compatible or not. It should be noted that just because a manufacturer does not endorse the use of E10 with a particular vehicle, this does not mean it will have problems if operated on E10. There were very few problems with E10 in the US when it was introduced in the late 1970s, even though most of the vehicle fleet had not been designed for its use.

Ethanol is a clean-burning fuel that produces fewer air-quality-related emissions. In terms of GHG emissions from the tailpipe, it is only slightly better than petrol. However, as the crop that was used to produce the ethanol grew, it removed an equivalent amount of CO_2 from the atmosphere. Thus, the critical issue is how much energy is consumed in producing and distributing the ethanol, compared to what is used in extracting, refining and distributing the petrol.

The most currently used biodiesel is fatty-acid methyl ester (FAME), which is produced from vegetable oils or animal fats by a chemical process called transesterification. Although it can be used as a substitute for diesel fuel, it is chemically quite different and has different properties. Recently, a new process for making a diesel fuel from biomass has been developed, and is called non-esterified renewable diesel (NERD). NERD is chemically very similar to petroleum-based diesel, and thus overcomes the few problems associated with FAME.

As with ethanol, biodiesel is usually blended with petroleum-based diesel to produce a fuel, although it is quite possible to use pure biodiesel as a fuel. The most common blends are B5, which is widely used in Europe, and B20, which is used in the US. The main differences between FAME and petroleum-based diesel relate to compatibility with materials, melting point, lubricity and cetane value (de Pont 2006). Two of these factors are positive and two are negative. Some of the rubber materials used as seals in the fuel systems of older diesel engines are not compatible with FAME. All diesel fuel solidifies as the temperature is reduced, and thus various additives are used for cold-weather applications. FAME solidifies at higher temperatures, and thus is potentially more susceptible to problems in colder climates. The critical temperatures vary with the feedstock used to produce the FAME, and FAME based on animal fat (tallow) typically has a higher melting point (causing more problems) than FAME based on vegetable oils. Lubricity refers to the fuel's ability to lubricate the moving parts in the fuel delivery system (pump, injectors and so on). The reduction in sulphur content in petroleum-based diesel reduced its lubricity, and many older diesel engines had problems as a result. FAME improves lubricity and overcomes these problems, even at a very low level of blending (B2). FAME has a higher cetane rating and is a cleaner-burning fuel than petroleum diesel, producing fewer particulate emissions, less CO, and fewer unburned hydrocarbons. NO_x emissions may be slightly higher or lower, depending on the engine configuration and testing procedures. Fuel efficiency is very similar, and so GHG emissions at the tailpipe are similar. Reductions in GHG emissions occur because the biomass used to make the biodiesel extracted the CO_2 from the atmosphere as it grew. As with ethanol, the effectiveness of this depends on the amount and type of energy consumed in growing, processing and distributing the biodiesel.

Barriers

The use of biofuels as a substitute for petroleum-based fuels has been criticised by a number of commentators, for the following three main reasons:

- Lack of effective emissions reduction: It is argued that the additional energy consumed in producing the biofuels erodes all of the gains in GHG emissions.
- Substitution of food crops: It is argued that land that would otherwise be used to grow food crops is being used to grow biofuel feedstocks, driving up food prices and contributing to food shortages.
- Land-use conversion and destruction of carbon sinks: It is argued that forests are being cut down to create cropping land for growing biofuel feedstocks, and that the forests would have absorbed more CO_2 than the replacement crops.

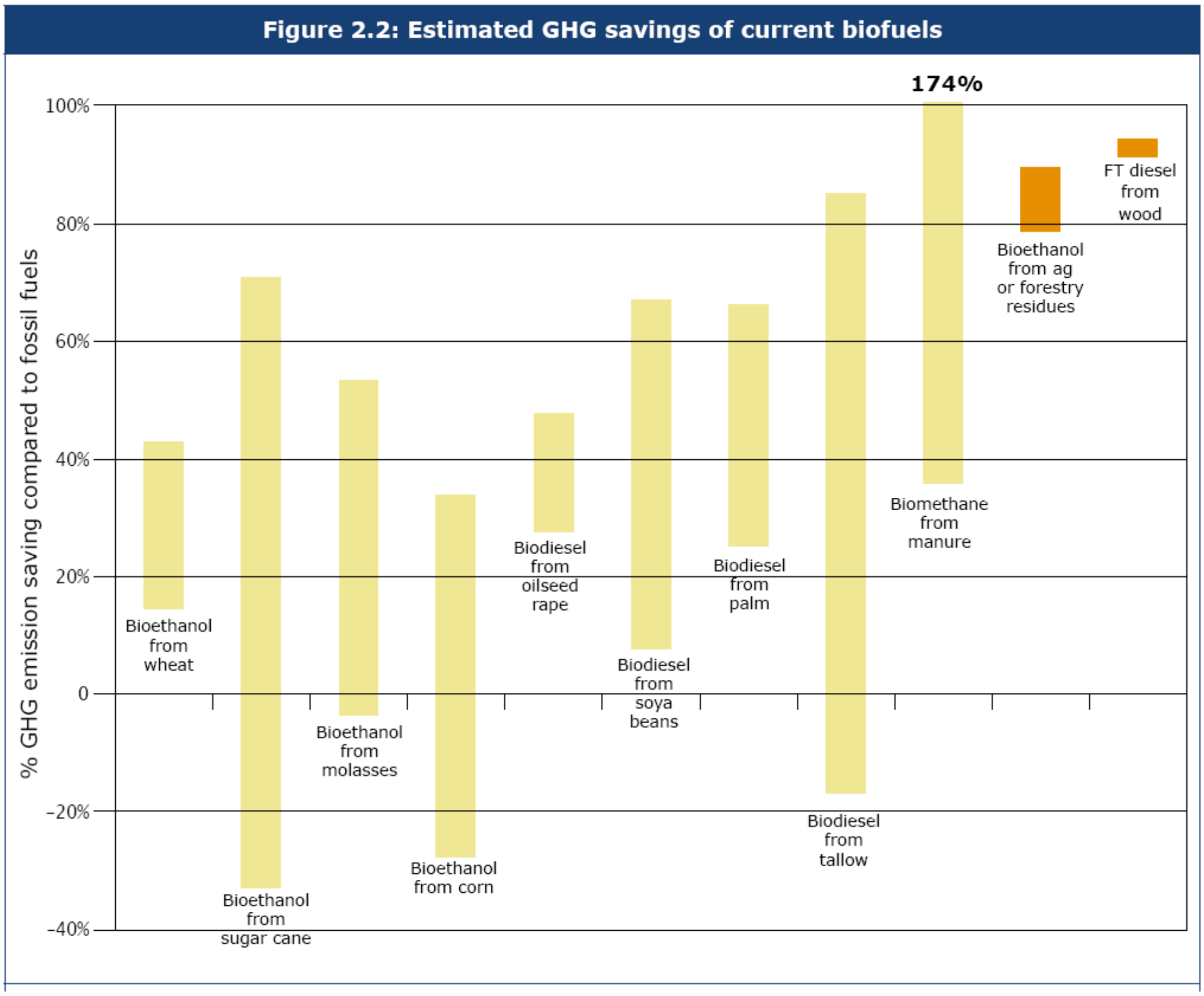
In response, the UK government commissioned a review of the indirect effects of biofuels (Gallagher 2008). Although the criticisms have validity for some of the biofuels that are produced, they do not apply to all of them. Furthermore, considerable research and development effort is going into new methods of producing biofuels that overcome these problems. These are the so-called '2nd-generation' biofuels. Figure 5.1, which is reproduced from the Gallagher report, shows the wide range of performance of existing biofuels, and the performance of the 2nd-generation biofuels. Thus ethanol from sugar cane can, in the worst case, cause a 35% increase GHG emissions, while in the best case, it can produce a 70% reduction. The superior performance of the two 2nd-generation biofuels (coloured orange) is clear, although it is also clear that methane produced from manure can perform extraordinarily well in this regard. This is because one tonne of methane is rated as equivalent to 25 tonnes of CO_2, whereas once it has been used as fuel, it is converted to CO_2 – thus one tonne of methane becomes approximately 2.75 tonnes of CO_2.

The values shown in figure 5.1 include all the life cycle emissions, but do not include any emissions associated with land-use change. Many land-use changes will incur an initial loss of carbon that must then be recovered from the use of the biofuel before there is a net benefit. Depending on the type of land-use change, this period can be quite long – sometimes decades or even centuries. Again, 2nd-generation biofuels tend to focus on reducing the use of productive arable land. This is done through higher-yield crops, the use of waste products, and the use of marginal lands.

The third issue is competition with food production. This occurs in the following two main ways:

- The feedstock crop itself may be edible, or used as animal feed. Demand for biofuels will therefore raise its price and reduce the food supply.
- The biofuel feedstock crop may be more valuable and divert resources such as land, water, fertiliser and labour away from food production. Second-generation biofuels will reduce the resources needed for production of food, but the issue of diverting labour may still be important.

Figure 5.1 GHG emission reductions for different biofuels (Gallagher 2008)



In the UK, the Renewable Fuels Agency (Goodall 2009) has also developed a methodology for carbon and sustainability reporting that quantifies the environmental and social impacts of different biofuels, as well as the carbon savings achieved. By insisting that biofuels are rated using this type of methodology, and using only biofuels that have acceptable ratings, it is possible to ensure that the overall aims of biofuel use are achieved.

5.6.3 Gas

Gas has been used as a transport fuel for many years. The two main forms are compressed natural gas (CNG) and liquefied petroleum gas (LPG). CNG is primarily methane, the lightest of the hydrocarbons, while LPG is usually made up of propane and/or butane. Both are fossil fuels, although methane is also produced from various forms of biomass, including manure, rubbish and decaying vegetation. As methane emissions have a very high CO_2-equivalency factor, capturing this biomethane and using it as a fuel (which converts it to CO_2) can have a large positive impact on GHG emissions, as illustrated previously in figure 5.1. Natural gas can also be transported in liquid form (LNG). Although this requires quite low temperatures and lower pressures than CNG, it does achieve higher densities and is used for the bulk transport of the fuel. To date, LNG has been used as a fuel for heavy vehicles, but not for light vehicles.

Both fuels burn cleanly and have good performance with respect to air-quality emissions. Both have higher energy content per kilogram of fuel than petrol, with CNG being slightly better than LPG. The energy density depends on the ratio of hydrogen to carbon – the higher the better. Theoretically, this means that these fuels should produce fewer GHG emissions for a given level of energy output. The extent to which this is achieved in practice depends on the efficiency of the engine using the particular fuel. Typically, for engines that are dedicated to the gas fuels and optimised for them, gains of 15–30% are achievable (Simpson 2004; Lane 2006; Green and Schafer 2003). Often, vehicles are operated as 'dual fuel' and can be switched to use either gas or petrol. Usually these engines are designed for petrol use and are not optimised for gas, so the reduction in GHG emissions is less.

The main drawback of these fuels is their relatively low density. Natural gas is very light, which adds to its safety because, in the event of a leak, it disperses rapidly. However, containing a sufficient quantity of fuel within an acceptable volume requires it to be stored at either a relatively high pressure, or in liquid form at a relatively low temperature. Typically, in gaseous form CNG is stored at 200bar or more, while in liquid form LNG requires a temperature below -163°C. The pressure used for CNG is similar to that used for scuba tanks. Thus the tanks required are quite heavy and need to be tested regularly. Even so, the volume of gas that can be accommodated is limited, and typical CNG installations in cars have a range of only 150km or so.

LNG is more difficult to handle and has not been used for light vehicles. It is used to facilitate the bulk transport of natural gas by ship, and to a limited extent has been used as a fuel for buses and other heavy vehicles. Although LPG is not quite as energy intensive as CNG, it liquefies at modest pressure (about 8bars), and thus the storage requirements are less demanding. It is also significantly denser and thus a substantially greater range can be achieved for the same volume, although this range is still significantly lower than the range achievable for the same volume of petrol.

In the late 1970s and early 1980s, the New Zealand government actively encouraged the use of CNG and LPG through subsidising the establishment of refuelling facilities, and providing interest-free loans for car owners to fit dual-fuel systems. They also specified that their own fleet vehicles should be CNG-powered (in the North Island only, as CNG was not available in the South Island). This was remarkably successful – by 1985, more than 100,000 CNG conversion kits had been fitted to cars, and by 1987, 50,000 LPG-fuelled cars were operating, out of a total fleet of about 1.5m (Dominion Post 2008). The subsidies were removed in 1984, although the fuel excise duty on CNG and LPG has remained lower than that on petrol. The reduction in government support, together with lower petrol prices, has led to virtual elimination of CNG as a fuel in the light-vehicle market. Very few CNG fuelling facilities remain operational and so, unless there is a substantial investment in the distribution network, the potential for a revival of CNG is limited. LPG use also declined substantially, but because the distribution network also supplies home barbecues and heating appliances, it has continued to function and there are a modest number of LPG-fuelled vehicles still operating, particularly in taxi fleets in the major urban centres.

Both Ford and Holden offer new LPG-fuelled vehicles. The Ford Falcons are a dedicated LPG vehicle (that is, they are not dual fuel). They cost slightly more than the petrol equivalent (NZ$400–$1500, depending on the model), have poorer fuel consumption (on a litres/100km basis), but a greater range and cost less to run (Ford Motor Company 2009). Their rated CO_2 emissions are slightly lower than the petrol equivalents – 244g/km compared to 255g/km (Ford Motor Company 2009). The Holden option is a dual-fuel vehicle, and is about NZ$4700 more expensive than the comparable petrol-only vehicle (Holden 2009). Because it has two fuel systems, its range is substantially higher than that of the petrol-only version. Because the engine design cannot be optimised for both LPG and petrol, we would expect the fuel efficiency and emissions performance to be inferior to the Ford's. The official fuel economy figures support this contention, but the differences are small.

5.6.4 Synthetics

We have already discussed fuels synthesised from biomass, but there are also automotive fuels that can be synthesised from other (generally non-automotive) fuels. Perhaps the best-known of these synthesis processes is the Fischer-Tropsch (FT) process developed in Germany in the 1920s. This process is the catalytic conversion of synthetic gas (a mixture of carbon monoxide and hydrogen) to a liquid hydrocarbon fuel. The composition of the FT liquids can be altered by controlling the process conditions, and thus the fuel can be made as a substitute for either petrol or diesel. In practice, most current FT fuels are diesel substitutes, with significantly cleaner air-quality emissions characteristics. Their big advantage is that they can be used interchangeably with petroleum-based diesel, without any engine modifications. It is also possible to blend them with petroleum-based diesel.

In terms of GHG emissions, the performance of FT fuels depends on the feedstock and the process used to produce the synthetic gas. The fuel itself is virtually functionally identical to diesel, and produces the same level of CO_2 emissions in combustion. The most common feedstock is coal, although natural gas or biomass can also be used. Van Vliet et al (2007) claimed that the FT process using coal emitted more CO_2 than refining diesel from crude oil, but that if carbon sequestration was used, it had similar emissions to refining. On the other hand, Gray and Tomlinson (1997) presented an analysis that showed that FT diesel produced from a mixture of coal and natural gas with electric power co-generation would result in lower CO_2 emissions per distance travelled than conventional diesel.

An alternative to FT diesel is dimethyl ether (DME). This also is produced by a chemical process applied to coal, natural gas or biomass. DME is also a very clean-burning fuel that can be used in diesel engines. However, it is a gas at room temperature and atmospheric pressure, and requires some pressure to liquefy it. Conveniently, the pressure required is similar to that of LPG, and the fuel distribution systems that are used for LPG can also be used for DME. An analysis by Celik et al (2004) showed that with co-generation and carbon sequestering, DME from coal could produce lower CO_2 emissions per vehicle-kilometre than conventional diesel. The gains were of a similar magnitude to those claimed for FT diesel with co-generation.

It would appear that FT diesel and DME both have a similar emissions performance, so the main drivers for choosing between them will be economic. In both cases, emissions performance superior to conventional diesel can be achieved, but only if electric co-generation occurs at the manufacturing facility (that is, some of the waste energy is recovered) and carbon sequestration is applied.

5.6.5 Hydrogen

We have already discussed the use of hydrogen in fuel cells. It is also possible to use hydrogen in ICEs. Hydrogen burns very cleanly and emits no CO_2. Hydrogen can be produced by electrolysis, and thus if the electricity used is generated from renewable resources, we can achieve a zero-emissions vehicle. However, it is more energy-efficient to produce hydrogen from hydrocarbons such as methane (natural gas), but in this case, there are carbon emissions.

The main problems are in the storage and distribution of hydrogen. Hydrogen is the lightest of all gases and thus occupies large volumes. To transport sufficient quantities to provide a reasonable range, we need to either apply very high pressures, or very low temperatures to make it liquid. The boiling point of hydrogen is approximately -253°C. At 800bar pressure, the density of gaseous hydrogen is about the same as that of liquid hydrogen at 70kg/m^3. This is still only about 10% of the density of petrol. Hydrogen has just over three times the energy density of petrol (143MJ/kg, compared to 46.4MJ/kg), so for the same total amount of energy, about three times the volume of hydrogen is required.

Bossel et al (2003) argued that hydrogen should be considered as a carrier of energy, rather than as a fuel. The rationale for this was that hydrogen does not occur naturally and must be manufactured either from energy (electricity in an electrolysis process), or from another fuel, such as natural gas. When the hydrogen is used, the energy or fuel that was used to make it is consumed. Furthermore, they posited that hydrogen is an inefficient carrier compared to its sources because of energy losses in the conversion processes. That is, it is far more efficient to distribute the electricity or natural gas than it is to distribute hydrogen. It is difficult to argue with this analysis. If the fuel is to be used in an ICE, then it is clearly more efficient to use the natural gas directly than it is convert it to hydrogen and then use the hydrogen. The same argument applies to fuel cells. From a GHG-emissions perspective, it may be better to use hydrogen if the carbon produced in the conversion process can be sequestered. However, there is a significant energy consumption penalty.

6 Current fleet and travel patterns

6.1 The New Zealand light-vehicle fleet

The Strategy and Sustainability Group at the Ministry of Transport has undertaken an analysis of the New Zealand vehicle fleet – the results are available for downloading, in spreadsheet form, on the Ministry's website (Ministry of Transport 2008d). The most recent version of this analysis is dated July 2008, and contains data up to the end of 2007. The data that is relevant to this study has been extracted and reproduced here.

Figure 6.1 shows the proportion of vehicle kilometres travelled by the different vehicle categories. This shows the dominance of the light-vehicle fleet and explains why this study has targeted light vehicles.

Figure 6.1 Travel in 2007, reproduced from Ministry of Transport data (2008d)

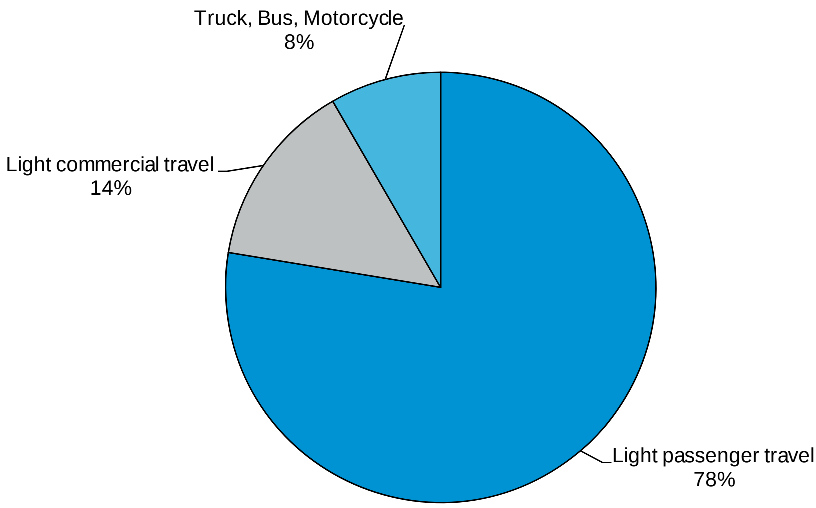


Figure 6.2 shows the age profile of the light-vehicle fleet in 2007. This figure has been modified from the original to also include the data for all light vehicles. The shape of the New Zealand distribution in 2007 was different from that of most other countries because of the effect of used imports from Japan, which resulted in the peak being at 10-year-old vehicles, rather than at new vehicles. This also resulted in the New Zealand fleet having a relatively high average age compared to other countries.

This average fleet age is often quoted as a problem in terms of the time it will take for new technologies to permeate through the fleet. However, the main reason for the high average age was that newer cars (less than five years old) were under-represented, rather than older cars being over-represented. For example, the average age of the New Zealand light passenger vehicle fleet was 12 years, compared to 9.7 years for the Australian fleet (Australian Bureau of Statistics 2009). However, the proportion of vehicles over 15 years old was 22% in New Zealand, compared to 21.2% for the Australian fleet. Thus, although the initial market penetration of any new technology into the New Zealand fleet will be slower than in Australia, the time to achieve 80% penetration will be similar.

Figure 6.2 Age distribution of the light-vehicle fleet (adapted from Ministry of Transport 2008d)

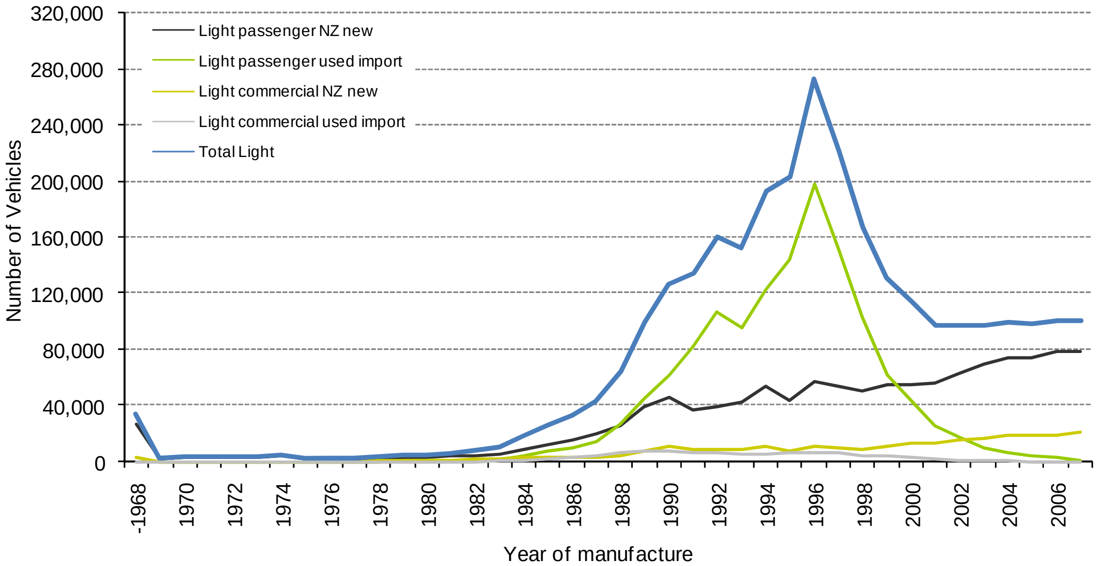


Figure 6.3 shows the distribution of engine sizes in the fleet at the end of 2007. Just over 60% of the fleet had an engine size between 1600cc and 3000cc, with 26% having smaller engines and 13.5% having larger engines.

Figure 6.3 Distribution of engines sizes in the light-vehicle fleet at the end of 2007 (Ministry of Transport 2008d)

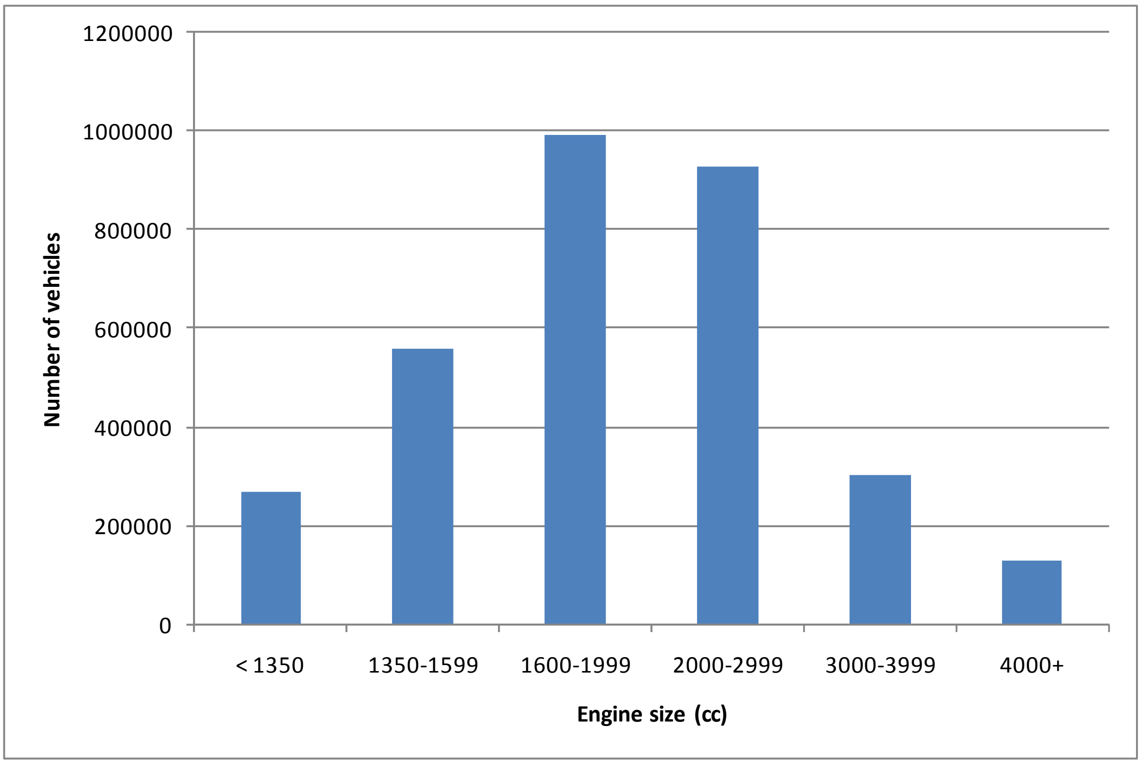
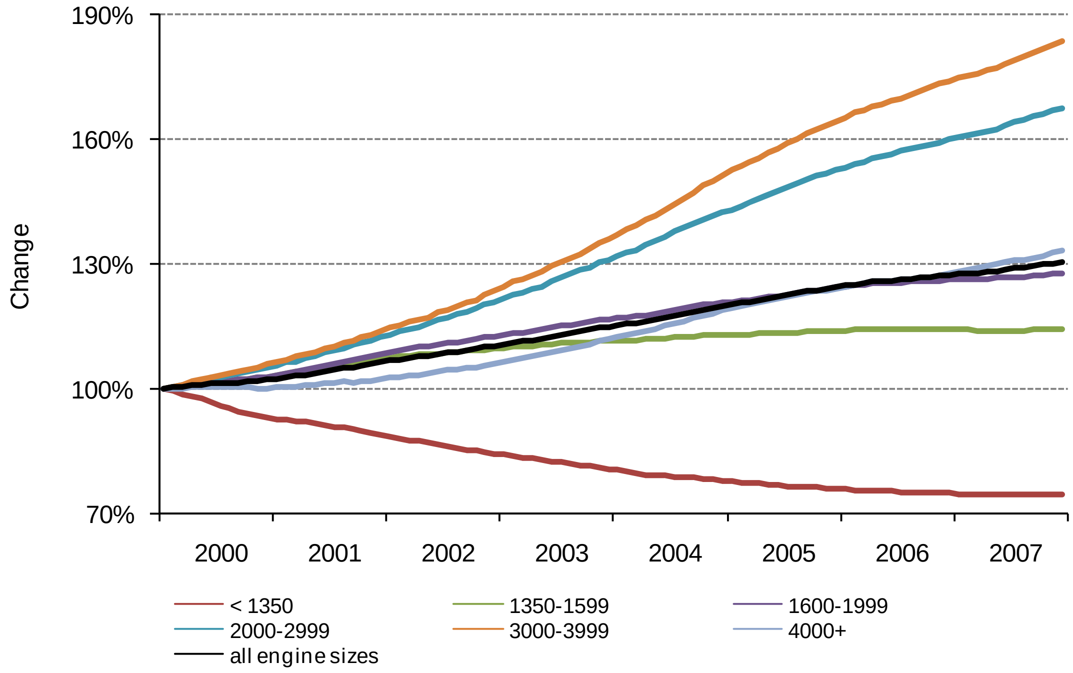


Figure 6.4 shows the trend in engine size choice from 2000–2007. Again, the data for all vehicles has been added to show the relative changes. Vehicles with small engines (less than 1350cc) substantially

declined in popularity. The next engine size up (1350–1599cc) also declined in popularity (the growth in numbers was less than the average growth). 1600–1999cc engines and 4000cc+ engines increased at approximately the same rate as the average, while 2000–2999cc and 3000–3999cc engines grew in popularity. Overall, motorists were tending to choose larger-engined cars.

Figure 6.4 Trends in engine size 2000–2007 (adapted from Ministry of Transport 2008d)



Figures 6.5 and 6.6 show the annual kilometres travelled in 2007 by light passenger and light commercial vehicles respectively, by age of vehicle disaggregated by engine size. For light passenger vehicles, the trends are straightforward and clear. Annual distance travelled increased with newer vehicles and with larger engine sizes. With older vehicles (more than 17 years old), the effect of engine size was negligible and, if anything, the largest-engined vehicles travelled less. The situation with light commercial vehicles was slightly more complicated. The age effect was the same, with newer vehicles travelling greater annual distances, but the engine-size effect was different – the greatest annual distances were travelled by vehicles with engines between 2000cc and 2999cc. The larger-engined vehicles (3000+cc) travelled less.

There are several possible reasons for this, including:

- fuel type – proportionately more commercial vehicles are diesel and there are few large diesel-engine light vehicles available
- economics – commercial vehicles are more likely to be selected on a strictly financial assessment.

As with the passenger vehicles, engine size had little effect on travel for older vehicles. The annual distance travelled for the smaller-engined vehicles varied significantly from year to year of age. It is likely that this is a statistical sampling error because of the relatively small numbers of vehicles in those categories.

Figure 6.5 Travel by light passenger vehicles for 2007 by vehicle age and engine size (Ministry of Transport 2008d)

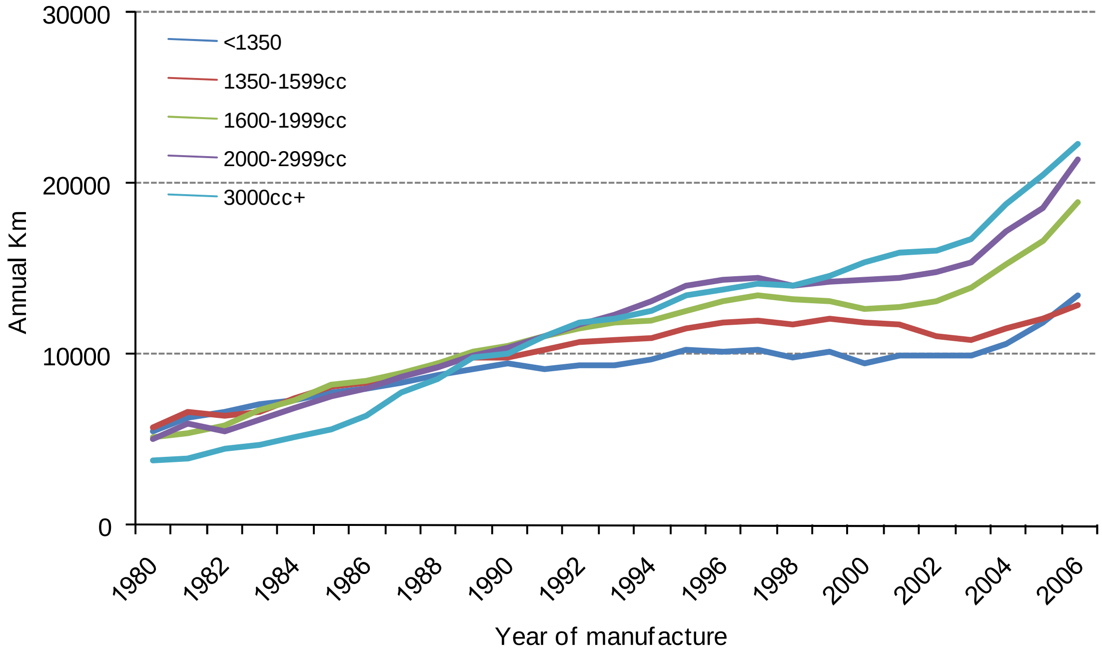
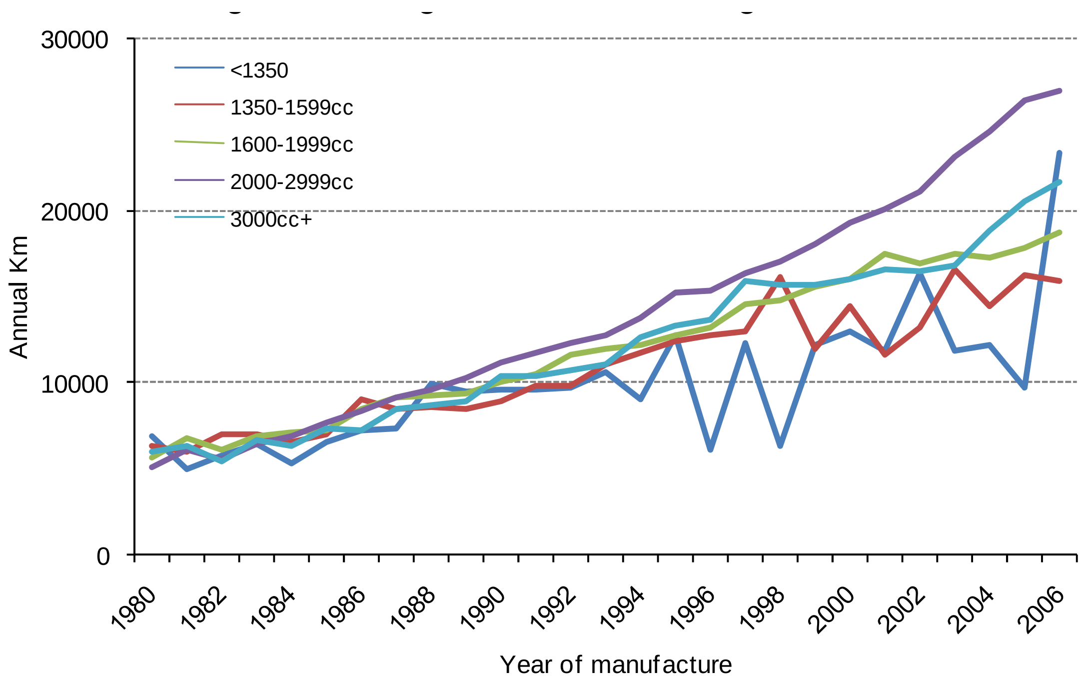


Figure 6.6 Travel by light commercial vehicles for 2007 by vehicle age and engine size (Ministry of Transport 2008d)



Figures 6.7 and 6.8 show the split between diesel and petrol vehicles, by vehicle numbers and kilometres travelled respectively, for both the light passenger and light commercial fleets in 2007. Commercial vehicles made up 12.5% of the fleet but 15.3% of the kilometres travelled. For commercial vehicles, diesel engines made up 62% of the fleet but accounted for 71% of the travel; while for passenger vehicles, diesel

engines made up only 8.5% of the fleet but accounted for 10.4% of the travel. Overall, diesel vehicles made up 15.2% of the fleet and accounted for 19.6% of the distance travelled.

Figure 6.7 Light-vehicle numbers by fuel type (Ministry of Transport 2008d)

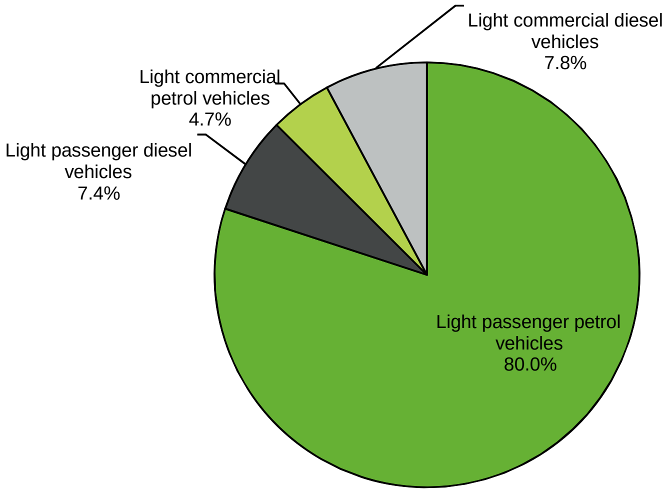
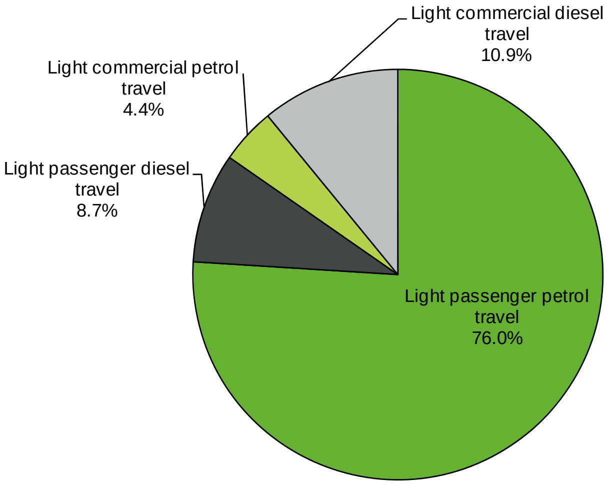


Figure 6.8 Light-vehicle travel by fuel type (Ministry of Transport 2008d)



6.2 Travel behaviour

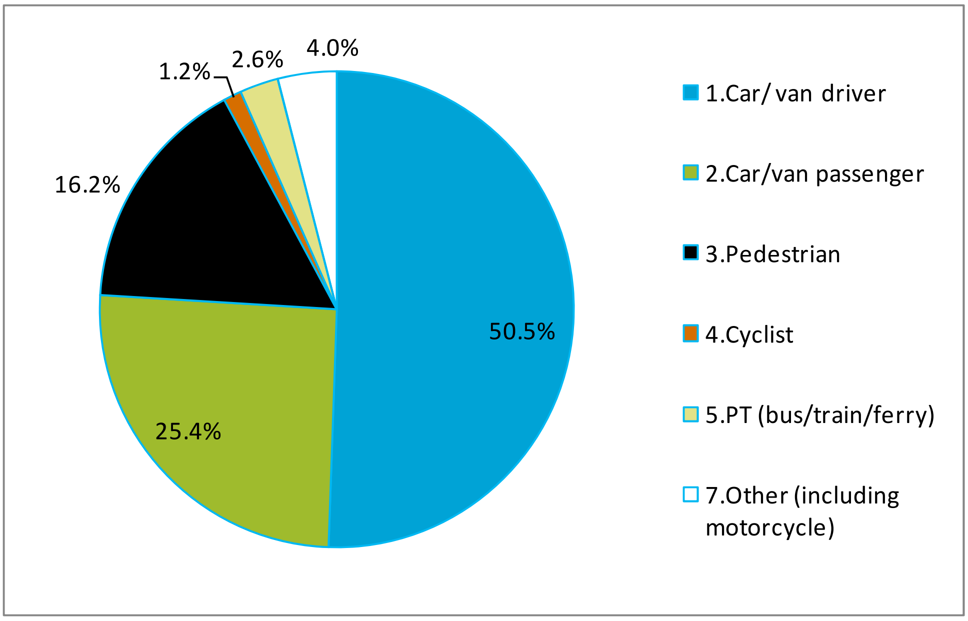
New Zealand's Ministry of Transport conducts a household travel survey on an annual basis. This survey samples 2800 households and provides a snapshot for that year of travel behaviour in New Zealand. Relevant results derived from the most recent survey are reproduced below.

Travel data was collected in terms of number of trips made, time spent travelling and distance travelled. All three aspects of travel are considered relevant to determining possible options for changing travel behaviour to achieve better fuel efficiency and lower emissions. The latest data (Ministry of Transport 2008b) was analysed to produce figures 6.9–6.11, which give the modal split for each of the three aspects. The modal split by distance (figure 6.11) is slightly distorted because there is no data for the distance travelled by 'Other'. Thus the percentages attributed to the remaining modes are slightly high, although the relativities are correct.

The most striking aspect of the data was the dominance of the car as a mode of transport in New Zealand households, accounting for more than 75% of trips. The data by number of trips and time walking was also significant, although obviously as proportion of distance, it was very small. The bicycle, which is the most efficient and lowest-emission vehicle, had only a very minor role in household travel in New Zealand.

Public transport use was also very low by international standards. For example, if we consider trips to work, 6% of trips in New Zealand included a public transport component. In Australia, 14% of people use public transport to travel to work (Australian Bureau of Statistics 2008). On the other hand, the US, in 2000, recorded 9403M public transport trips for a population of 281.4M; that is, 33.4 trips per person per year (Pucher 2002), while the New Zealand figures for the 2003–07 period were 45.7 trips per person per year. In the EU27 (the 27 countries currently belonging to the European Union), 10.9% of passenger-kilometres are by bus/coach or tram/metro, with a further 6.9% by rail (European Commission 2009). This report gives a comparable figure for the US of 3.7% for all bus and rail, while for New Zealand only 3.3% of passenger-kilometres were by public transport modes (figure 6.11).

Figure 6.9 Modal split by number of trips



It was useful to investigate the nature of this travel, in order to identify opportunities for improving the fuel efficiency and reducing the emissions associated with it. Car occupancy was analysed by region. It did not vary much from region to region (the range was 1.48–1.88, and reduced to 1.59–1.72 if three outliers were removed), and the average for the country was 1.65. The data was also used to calculate average trip times, average trip distance, and average number of trips per person per day, for each of the modes. The results of this are shown in table 6.1.

Figure 6.10 Modal split by time spent travelling

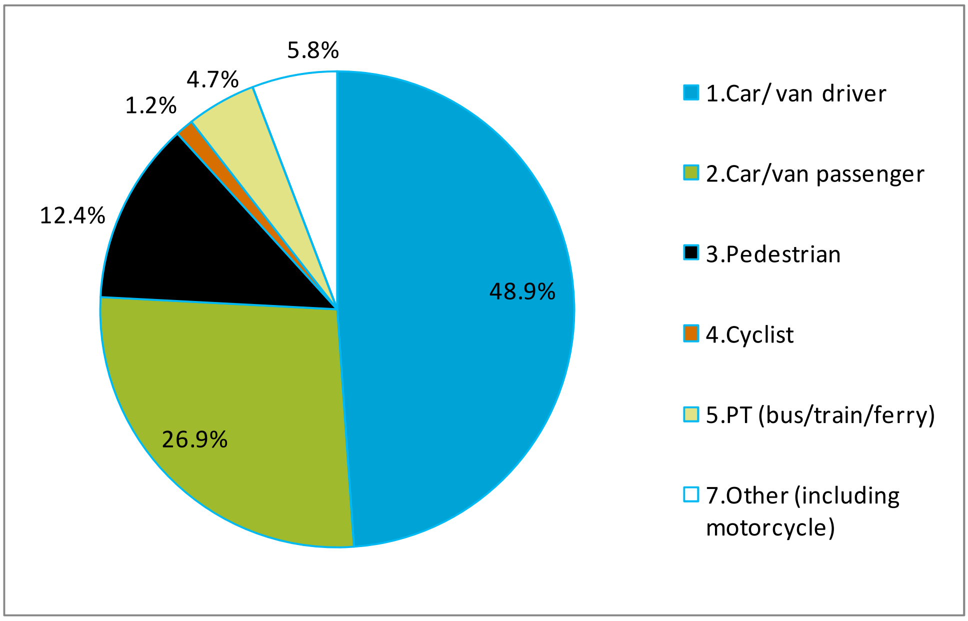


Figure 6.11 Modal split by distance travelled

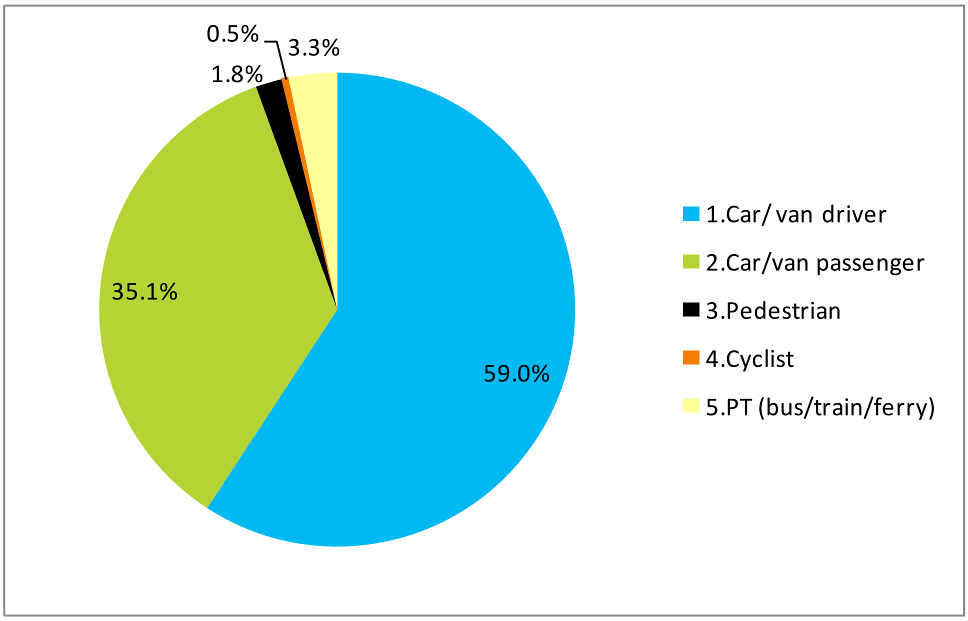


Table6.1 Average trip characteristics derived from the Ministry of Transport's household travel survey (2008b)

	Car/van driver	Car/van passenger	Pedestrian	Cyclist	PT (bus/train/ ferry)	Other (incl. motorcycle)	Total
Trips/person/day	2.41	1.21	0.77	0.06	0.13	0.19	4.78
Minutes/trip	14.6	16.0	11.6	15.3	27.1	21.9	15.1
Km/trip	9.0	10.7	0.9	3.0	9.7		7.8

The Ministry of Transport also analysed the data to determine the distribution of distance travelled per day by light vehicles. The results of this analysis are shown in table 6.2. It needs to be remembered that this data came from a household travel survey and thus reflected private motor vehicle use, and not commercial vehicle use. However, if we refer back to figure 6.6, we can see that, on average, commercial vehicles travelled between about 5000km and 25,000km per year, depending on vehicle age and engine capacity. If we assume that these vehicles were used only 250 days per year, the average daily distance travelled ranged between 20km and 100km. If they were used on more days, the average daily distance decreases.

Table 6.2 Distribution of distance travelled per day by privately owned vehicles

	Km per light, privately owned vehicle per day							
Area of residence	**mean**	**median**	**5th percentile**	**10th percentile**	**25th percentile**	**75th percentile**	**90th percentile**	**95th percentile**
All New Zealand	39.0	23.2	3.0	4.9	10.7	46	84	126
Main urban areas	34.9	21.6	3.3	5.3	10.7	41	69	106
Secondary urban areas	37.9	16.1	2.6	4.1	7.0	43	97	153
Rural areas and towns with population <10,000	52.2	33.6	2.3	4.1	11.7	70	118	168
Vehicle type								
Car/station wagon	37.2	22.1	3.0	4.8	10.3	44	79	121
SUV	48.0	28.5	3.7	6.1	12.5	58	108	158
Van/ute	45.0	28.5	2.9	5.7	12.9	52	93	143

7 Potential benefits of specific fleet changes

7.1 Introduction

In the review of different vehicle types, we identified three broad vehicle categories – human-powered, low-powered and standard vehicles – in increasing order of fuel consumption and emissions output. Within each category, there are a range of vehicle configuration possibilities and fuel options. Generally speaking, if trips can be transferred from one vehicle category to a lower vehicle category, there will be a reduction in fuel consumption and emissions. However, within vehicle categories there are also potential gains through smaller vehicles and alternative fuels. These gains may be as high as those achievable from changing vehicle categories. Moreover, it is likely to be easier to persuade people to change travel behaviour by changing vehicles within a category than it is to persuade them to change categories. Changing from a larger car to a smaller car is easier than changing from a small car to a moped or a bicycle.

To determine the benefits from changing vehicles, we need to compare the performance of the alternative vehicle options. A variety of methods have been used for this including, in order of increasing complexity, tank-to-wheels analysis[4], well-to-wheels analysis[5], and life cycle analysis[6]. Although it might appear that the best approach is to apply the full life cycle analysis to all the options being considered, the increasing complexity also results in greater uncertainty and less reliability in the results. There are also issues of scope; that is, deciding what needs to be included and where to set the cut-off boundaries. For example, in considering the energy and emissions associated with making the vehicle, should the energy and emissions generated by the workers in travelling to and from the plant be included or not?

When comparing two alternatives, the simplest method that is satisfactory will provide the greatest accuracy. Thus for comparing alternative fuels that are similar in nature, such as petrol and diesel, it may be sufficient to consider a tank-to-wheels analysis. If the engine technologies are similar but the fuel production methods are very different, such as when comparing petrol with bioethanol, it is probably necessary to consider a well-to-wheels approach; while if the vehicle technologies are completely different, such as when comparing battery electric vehicles with conventional petrol cars, a life cycle approach is likely to be needed.

7.2 Life cycle modelling approaches

Fletcher et al (2007) developed a methodology for giving cars an environmental rating. This received considerable newspaper publicity (Anon 2007b; Reed 2007; Reguly 2007), primarily because the Toyota Prius hybrid petrol–electric, which is promoted as very environmentally friendly, did not lead the rankings.

Fletcher et al’s method was to give each vehicle an environmental rating based on published emissions data. This was based half on GHG emissions, and half on air-quality emissions. Each vehicle was also given a footprint rating based on length, width and weight (multiplied together). The overall rating was determined by multiplying the environmental rating by the footprint rating. To score the vehicle, the inverse of the rating was used, so that ‘greener’ vehicles achieved a higher score. The footprint rating was

---

[4] A tank-to-wheels analysis considers only the emissions produced by the vehicle in consuming the fuel.

[5] A well-to-wheels analysis incorporates tank-to-wheels, but also includes the emissions associated with extracting, processing and transporting the fuel

[6] A life cycle analysis incorporates well-to-wheels, but also includes the emissions associated with manufacturing the vehicle and disposing of it at the end of its life.

intended to be a surrogate for the environmental costs of raw materials, manufacturing and disposing of the vehicle. The footprint calculation effectively penalised a vehicle in proportion to the 5th power of its length, or the 1.66th power of its weight. For example, if we scale a vehicle up by 10% in each dimension (length, width and height), we would expect it to be 1.1^3 (=1.33) times as heavy. By the Fletcher method, its footprint would be 1.61 times as high. It is difficult to see the rationale for this footprint factor. The vehicle would require 33% more raw materials to build, and it is unlikely that manufacturing and disposal would cost more than 33% more. Furthermore, by multiplying the environmental rating by the footprint rating, they magnified the overall effect. Using the same example as before, if the 10%-longer vehicle has 33% greater fuel consumption and hence 33% more emissions (the 33% increase is based on weight, and is conservative because aerodynamic drag will only have increased by 21%), then we might expect its overall rating to increase by 33%. However, using Fletcher's methodology, this vehicle's overall rating would increase by 114%.

The distortional effect of this scoring system is apparent when we compare the scores of some vehicles. The leading vehicle was the Smart Fortwo, which scored 53 points. In comparison, the Toyota Yaris 1.0 scored 29, while the Volkswagen Golf 1.9TDI scored only 12. The Smart had a rated fuel consumption of 4.7 l/100km, compared to 5.4l/100km for the Toyota and 5.0l/100km for the Volkswagen. Because the Volkswagen was diesel powered, it had a slightly (4%) higher CO_2 emissions rating than the Toyota, even though it had better fuel consumption. It is difficult to reconcile these scores with the vehicles' relative fuel efficiency and emissions characteristics. It should also be noted that the footprint measure did not take into account differences in vehicle technology at all. Weight was considered the same, regardless of whether it came from steel panels or NiMH batteries.

Also in 2007, another life cycle costing report, entitled *Dust to dust* (CNW Marketing Research Inc. 2006), was released in the US. This report came to the remarkable conclusion that over the life of the vehicle, a Hummer was more energy efficient than a Toyota Prius. The results of this report were published uncritically by the Reason Foundation (Dalmia 2006) and in an editorial in a student newspaper (Demorro 2007), and was then repeated and endorsed by two high-profile commentators in the mainstream media (Limbaugh 2007; Will 2007), which gave it an unwarranted credibility. Although the report was very long (458 pages), it contained almost no details on the methods or data sources used to derive its conclusions, and had obvious flaws. Several analyses discrediting the methodology and findings of this report were published – for example, Gleick 2007, and Hauenstein and Schewel 2007. However, even though these analyses were much more scientifically sound, they received much less media coverage.

The Argonne National Laboratory, a US Department of Energy research facility, developed a spreadsheet-based model, called 'Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation' (GREET), for calculating the life cycle energy use and emissions of a vehicle (Wang et al 2007). This model embedded data for more than 100 fuel production pathways and more than 70 vehicle/fuel systems, including the use of conventional and lightweight materials for the vehicles' construction. The spreadsheet format also enabled the user to investigate additional alternatives by replacing embedded default data with their own data. The GREET model was used by Hauenstein and Schewel (2007) in their analysis of the *Dust to dust* report. Outputs from the GREET model were energy consumption and emissions outputs by emission type. It did not attempt to generate an overall performance rating by combining results.

The GREET model split a vehicle's contribution to energy consumption and emissions output into three components:

- vehicle cycle – the contribution associated with the manufacture, assembly and disposal of the vehicle
- fuel cycle – the contribution associated with the production and distribution of the fuel

- vehicle operations – the contribution from operating the vehicle.

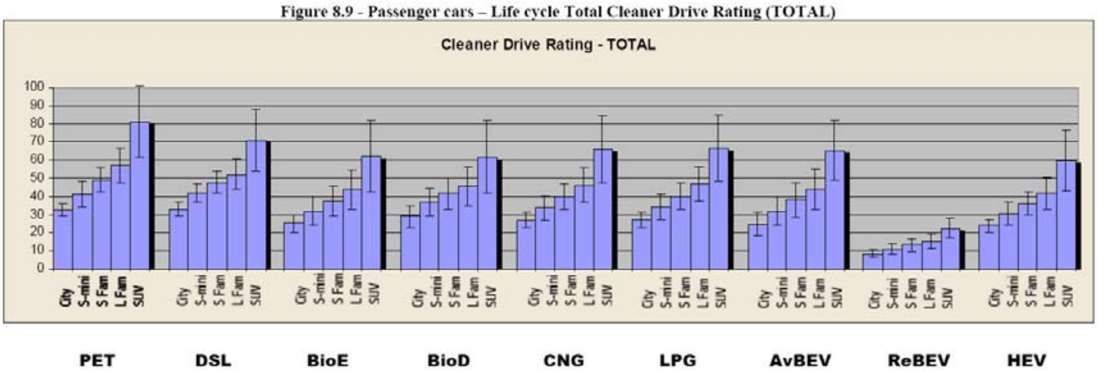
For a typical US petrol-powered car (GREET default values = the car weighed 1500kg, had an average fuel consumption of 10l/100km and a life of 257,000km), the contributions to energy used were 9.3% for the vehicle cycle, 18.2% for the fuel cycle and 72.5% for vehicle operations.

One of the options analysed in the default data in GREET used lightweight materials for the car (weight 840kg, fuel consumption 7.6l/100km and a life of 257,000km). This changed the proportional contributions to energy used to 11.7% for the vehicle cycle, 17.7% for the fuel cycle and 70.6% for vehicle operations. The total energy used per kilometre of travel decreased by 22%.

GHG emissions were almost exactly proportional to energy use for these two vehicle options, and thus the contributions of the three components of GHGs were nearly identical to their contribution to energy use. However, the contribution of the three components to other emissions was not proportional to the energy consumption of those components. For example, PM_{10} (particulate matter less than 10µm) emissions for the typical petrol car were the sum of a 49.7% contribution from the vehicle cycle, a 32.8% contribution from the fuel cycle, and only 17.4% from vehicle operations. Moreover, 72% of the vehicle operation contribution came from the tyres and the brakes, rather than the exhaust. This means that although diesel-powered vehicles produced more PM_{10} exhaust emissions than petrol-powered cars, exhaust emissions were only a very small contributor to total PM_{10} emissions. Furthermore, because the diesel-powered vehicle was more fuel efficient, the contribution per kilometre of the fuel cycle was less, and thus, with the default values in the GREET model, the overall impact on PM_{10} emissions of changing from petrol to diesel power was positive. This positive effect for diesel over petrol was actually true of all of the regulated (air-quality-related) emissions using the GREET default data. However, the default GREET parameters showed only small differences between the exhaust emission rates of petrol and diesel cars. If we run the GREET model with both vehicles having emission rates at the Euro IV limits, then the diesel-powered vehicle has better GHG emissions and better hydrocarbon and CO emissions, but worse PM_{10} and NO_x emissions. Running the GREET model at Euro V emission limits results in the diesel having superior performance in all respects except NO_x emissions.

In 2005, the London Borough of Camden commissioned Ecolane to undertake a life cycle assessment of vehicle fuels and technologies (Lane 2006). This study used a similar methodology to the GREET model to compare five generic different-sized passenger vehicles and two generic light commercial vehicles across nine fuel/engine technologies. The model was then also applied to a set of specific actual vehicles. The model traded off GHG emissions against air-quality emissions to determine an overall environmental impact score. The results for the overall rating of passenger vehicles have been reproduced in figure 7.1. The five passenger-car categories were: city car, super-mini, small family car, large family car and sports utility vehicle (SUV), as used by the International Federation of Automotive Engineering Societies (FISITA). The fuel/engine technologies were: petrol, diesel, bioethanol, biodiesel, CNG, LPG, battery electric vehicle using the average (UK) mix of electricity generation, battery electric vehicle using renewable electricity generation, and hybrid electric vehicle. The biofuel results were based on using 100% biofuel, not blends.

Figure 7.1 Overall environmental rating of generic passenger vehicles (Lane 2006)



Interestingly, the Toyota Prius was among the actual vehicles modelled and did not achieve the best ranking. It was beaten by the best of the petrol-powered city cars. However, the difference was quite small; the Prius scored 31, while the Citroen C1 scored 30. Intuitively, this relativity seems more reasonable than the large differences reported by Fletcher et al (2007). The best-performing vehicle was the Reva GWiz, which scored 22 when using average electricity, and 7 when using renewable electricity. The poorest-rated petrol-powered SUV scored 76, while typical petrol- or diesel-powered large family cars (these vehicles had 1.8- to 2-litre engines, which in New Zealand would be regarded as mid-sized rather than large) scored between 40 and 60.

From the results shown in figure 7.1, we can make some general comments:

- Generally, the environmental gains from downsizing the vehicle were at least as big as the gains from adopting an alternative fuel technology. The one major exception was ReBEVs, which provided large gains.
- For the smaller vehicles, there was very little difference between petrol and diesel. This is because the diesel vehicles are more fuel efficient and produce fewer GHGs, but at present, they also produce more air-quality-related emissions. In the model, these two effects balanced each other out.
- The fuel/engine technology options were based on current technologies in the UK. Thus, for example, the emissions associated with biodiesel production and distribution were based on using rape seed oil as a feedstock, with 50km of transport to the processing plant and 150km of road transport to the fuel stations. As was shown in section 5.6.2, the total net emissions performance of 2nd-generation biofuels is expected to be significantly better than the current 1st-generation fuels. This will have a substantial impact on the ratings of vehicles using these fuels.
- Similarly, the average electricity generation mix for the AvBEV vehicles was based on the UK, which is 37% gas-fired thermal, 35% coal-fired thermal, 22% nuclear and only 3% renewables. In New Zealand, approximately 70% of electricity is generated from renewable resources (Statistics New Zealand 2008). Thus the ratings for AvBEV vehicles in New Zealand should be much closer to those for ReBEV vehicles.

7.3 Well-to-wheels assessment

One of the complications in any comparison of vehicles is the question of whether the two vehicle options being considered are equivalent. In some cases this is straightforward. For example, to compare petrol and diesel power, there are Volkswagen Polo model variations with petrol and diesel engines that have similar engine power output and are virtually identical in terms of size and function. In other cases, it is more complicated. It has already been noted that a report that found that the Toyota Prius was less environmentally friendly than a Smart Fortwo attracted considerable media attention in the UK. However, the Toyota Prius is classed as a large family car, while the Smart Fortwo is a city car, and thus the two vehicles have quite different capabilities and are not equivalent. The issue becomes even more complicated when more radically different engine and fuel technologies are involved. For example, if we are comparing a battery electric-powered vehicle with a petrol-powered vehicle, do we expect them to have the same range and refuelling time? At the current state of battery technology, this is not practicable because of the weight and volume of batteries required.

Simpson (2004) undertook a well-to-wheels analysis, comparing 24 different well-to-tank fuel pathways, using computer simulation models of the vehicles. He attempted to address the comparability problem by using a petrol-powered Holden Commodore as the reference vehicle, and then configuring all the alternative fuel options to have the same performance and range. The only major exceptions were the battery electric vehicles using NiMH or VRLA (lead-acid) batteries, which were given ranges of 250km and 125km respectively, instead of the standard 500km. Even with the reduced range, the BEV with VRLA batteries was 83% heavier than the reference petrol vehicle. Simpson found that several of the fuel pathways produced higher energy consumption and/or higher GHG emissions than the reference vehicle. His main conclusions were as follows:

- The best way to utilise an energy feedstock is via a pathway that is as direct as possible, avoiding unnecessary energy conversions.
- Hybrid electric vehicles using conventional fuels (petrol or diesel) offer significant near-term reductions in energy intensity and GHG emissions.
- Natural gas is a promising transitional energy feedstock for automotive fuels, and using natural gas instead of petrol or diesel in hybrid electric vehicles further reduces their energy intensity and emissions. Using natural gas to generate electricity for BEVs produces the lowest GHG emissions of any natural gas-based fuel pathway.
- Pathways using electricity from renewable sources offer near-zero GHG emissions. However, renewable electricity should be utilised directly in electric vehicles, rather than converted into other fuels, because of the energy losses in conversion.

Simpson's analysis ignored vehicle-cycle effects. However, typically these are about 10% of the total effect and thus would not greatly affect his conclusions.

7.4 Tank-to-wheels

A tank-to-wheels analysis approach is only useful if the well-to-tank and the vehicle-cycle components are proportionately very similar. In most cases, the vehicle-cycle component is a relatively small proportion of the total (about 10%), and so minor variations in this do not have much effect. However, the well-to-tank component can vary substantially for different fuel types and pathways. Thus, typically a tank-to-wheels approach is mainly useful for comparing different vehicles using the same fuel, or very similar fuel.

MacLean and Lave (2000) undertook a study of the tradeoffs between air-quality and GHG emissions for different fuels, using a lifetime tank-to-wheels approach. Like Simpson (2004), they considered a standard reference vehicle and evaluated how it would perform with various fuels. They considered two range options for the vehicle (160km and 595km), eight fuel types, and three engine technologies. The eight fuel types were: petrol, California Phase 2 reformulated gasoline (this is petrol that is blended differently to produce lower emissions), diesel, E85 (85% ethanol and 15% petrol), E100, M85 (85% methanol and 15% petrol), M100 and CNG. MacLean and Lave noted that there were potential upstream tradeoffs associated with the production of the 'cleaner' fossil fuels, but they were unable to find published data and hence their analysis was limited to operational performance; that is, tank-to-wheels. Key findings were as follows:

- The lowest energy use for both vehicle range options was that of the direct-injection diesel-powered vehicle, at 74% of the baseline petrol-powered indirect-injection car.
- The lowest CO_2 emissions were produced by the CNG-powered direct-injection car using lightweight tanks, at 68% of the baseline. Diesel has proportionately higher carbon content than CNG and its emissions were 77% of baseline.
- Reducing the range improved the performance of the CNG-powered vehicles the most, because of the greater additional weight of the tanks for this fuel.
- Although some fuel technologies will have more difficulty than others in achieving air-quality emissions standards, all are expected to be able to do so. Hence air-quality emissions need not be a factor in vehicle/fuel choice.

7.5 Specific fleet changes

7.5.1 Introduction

In the early part of this report, we identified three broad categories of light vehicle:

- human-powered and human-powered hybrids
- low-powered urban vehicles
- standard vehicles.

These categories are listed in order of increasing fuel consumption and emissions output, although there is some overlap. Within each category, a number of vehicle, fuel and engine technologies are available. The review of the New Zealand vehicle fleet and travel patterns in section 6 can be used to identify opportunities for improved fuel efficiency and emissions performance.

In figures 6.9 and 6.10, we saw that in the Ministry of Transport's 2008 data, about 76% of household trips and 94% of household distance travelled in New Zealand were undertaken by car or van, and the role of other vehicles was minor. Therefore, the key to improving fuel efficiency and reducing emissions is improving the performance of the car and van fleet. The following three options are available for achieving this improvement:

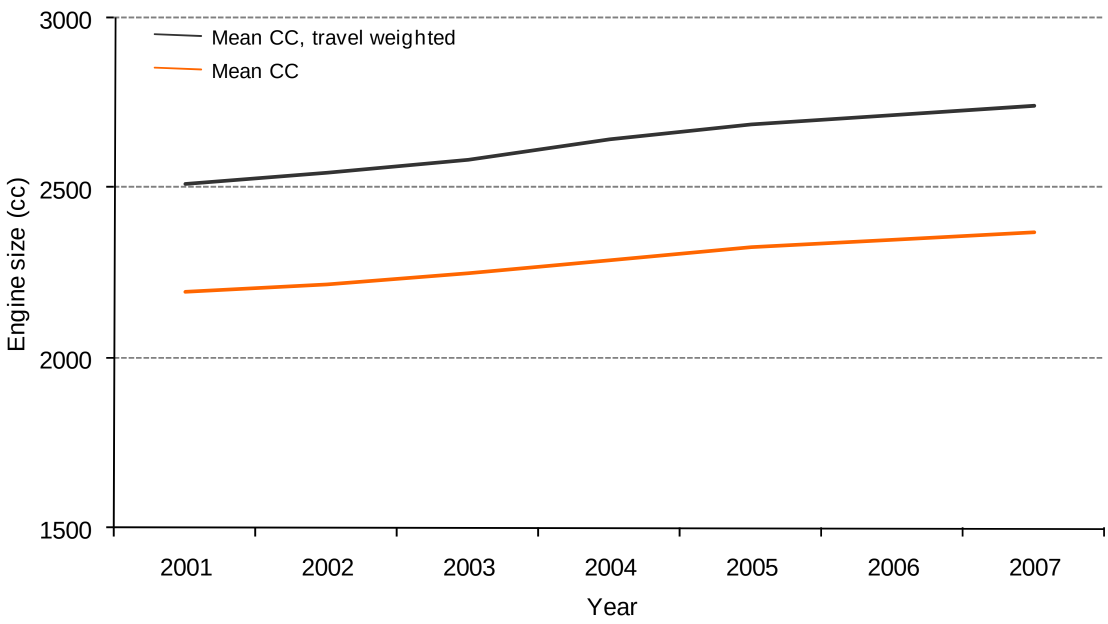
- using vehicles in the same category with the same fuel/engine technology, but with better fuel efficiency and emissions performance
- using vehicles in the same category, but using a different fuel/engine technology
- using vehicles from a lower fuel consumption/emissions category.

These options are not mutually exclusive and it is possible to use two of them together. We will now discuss the potential gains from each of these three options.

7.5.2 Better-performing vehicles of the same type

For the consumer, this represents the least change from the status quo and thus this is probably the easiest option to 'sell'. In figure 7.1, we can see than quite substantial gains in environmental performance can be achieved through reducing the size of the vehicle, particularly for the largest-vehicle categories. If we look at the New Zealand fleet data (figure 6.4), we see that the proportion of larger-engined vehicles (2000–3999cc) has been increasing and the proportion of smaller-engined vehicles (<1600cc) has been decreasing. The larger-engined vehicles also travel greater annual distances, and so the travel-weighted average engine size is higher than the actual average, as shown in figure 7.2. The average travel-weighted engine size in 2007 was 2700cc.

Figure 7.2 Trends in average engine size (Ministry of Transport 2008d)



Fuel consumption and GHG emissions performance are not directly related to engine size, but are more closely related to vehicle weight, although, in general, larger-engined cars are bigger and heavier. MacLean and Lave (2000) presented the following relationship between fuel consumption and vehicle weight for petrol-powered cars:

$$\frac{fuel\ economy_1}{fuel\ economy_2} = \left(\frac{weight_2}{weight_1}\right)^{0.72}$$

However, they said that this relationship assumed that a weight increase was accompanied by a powertrain modification, so that performance of the vehicles was equivalent.

In practice, the situation is more complicated. Although a vehicle's power requirements for a given level of performance are related to weight, larger engines will generally consume more fuel than smaller engines when the power demand is well within the capabilities of both engines. For example, in the US, the Toyota Camry is offered with two engine options – a 2.5l four-cylinder engine with a power output of 169hp (126kW), or a 3.5l six-cylinder engine with a power output of 268hp (200kW) (Toyota USA 2009). The six-cylinder model is only 4.7% heavier than the four-cylinder model, but for the standard fuel economy ratings, consumes 14–16% more fuel. The standard fuel economy ratings are based on defined driving cycles for city and highway operations, and thus are identical for both vehicles. Using the equation above, the additional weight would be expected to increase fuel consumption by about 3%. Thus, for the level of performance required by the standard drive cycles, the larger-engined model is less efficient. This situation can be reversed if the power demand is near the upper limit of the capability of the smaller engine.

For optimum fuel economy and minimum GHG emissions, the engine should have sufficient power to meet the demands of normal driving while operating in its fuel-efficient range. Additional power will enhance the vehicle's performance, but at the expense of fuel economy and GHG emissions, even when that additional performance is not being used. Reducing the vehicle's weight reduces the amount of power needed to achieve a particular level of performance. The highest speed limit in New Zealand is 100km/h and the maximum design grade on state highways is 10%, although there are roads with steeper grades than this. Even with a full load, the power required for a typical car to maintain 100km/h on a 10% grade is quite modest. EECA (2009) provided advice on the recommended engine size for different types of driving tasks. The largest recommended engine size was 2l, which was suggested for open-road use with three or four passengers. Most driving tasks can be undertaken satisfactorily with engine sizes between 1.2l and 1.6l. The EECA analysis did not consider towing a trailer and, for heavier trailers, larger engines would be needed to maintain speeds on hills.

The NZ Transport Agency publishes annual statistical analyses of vehicle registrations in New Zealand, and here we refer to *New Zealand motor vehicle registration statistics 2008* (NZTA 2009). To estimate the potential gains in fuel efficiency and GHG emissions from downsizing vehicles, we have considered the 10 best-selling makes and models of new cars in New Zealand in 2008. All of these makes and models have options for different engine sizes and levels of trim, and so on. For each make and model, we have considered one example of each engine size available (generally the lowest specification option), and where there were options for manual or automatic gearboxes, we chose the manual option. Data for vehicle weight, fuel consumption and emissions performance were extracted from the manufacturer's New Zealand websites for current models. This data is summarised in table 7.1.

From this data, we can calculate the potential fuel efficiency and GHG emissions gains from various vehicle-downsizing scenarios. For this analysis we will only consider the petrol-powered cars. The option to change fuel type is discussed in the next section.

The two vehicles in the 4000cc+ category are matched by vehicles in the 3000cc–3999cc category that are physically exactly the same size. Changing to the smaller-engined alternatives would have almost no effect on the functional capabilities of the vehicles, and would reduce fuel consumption and GHG emissions by 18–25%. However, these large vehicles make up only 4% of the fleet (4.8% by annual kilometres travelled). Thus, the overall effect at fleet level is about 1%. The same argument can be applied to nearly all of the vehicles in the 2000–2999cc category, in that there is a physically identical (or at least very similar) vehicle in the 1600–1999cc category. The gains in fuel efficiency and reduction of GHG emissions range from 8–15%. However, these vehicles make up about 37% of the fleet by vehicle-kilometres travelled, and so the fleet-level savings are potentially 3–5.5%. For most of the vehicles in the 1600–1999cc category, there is no directly comparable vehicle in the 1350–1599cc category, and so there is no option to downsize the engine without also downsizing the car. Thus the total potential fleet savings in fuel consumption and GHG emissions from downsizing engines, without downsizing car size, is about 4–6.5%.

The household travel data shown in figure 6.11 indicated that the average vehicle occupancy for household trips was 1.59. The average occupancy for business-related travel is likely to be even lower. Thus for most car users, it is not essential to maintain the physical size of the car. If we assume that the average fuel consumption and GHG emissions performance for a category is equal to the average of the vehicles shown in table 7.1, and we assume that all car users move down one category in engine size (the vehicles in the <1350cc category do not change), then the reductions in fuel consumption and GHG emissions range from 12–21%. If we weight the reductions using the annual distance travelled by each of the categories, we find that the potential reduction in fuel consumption and GHG emissions for the whole fleet is 14%. If we go a step further and assume that all car users move down two categories in engine size (the vehicles in the <1350cc category do not change and the vehicles in the 1350–1599cc category only change by one category), then the potential reduction in fuel consumption and emissions for the whole fleet is 22%.

Table 7.1 Summary of weight, fuel consumption and emissions for popular New Zealand cars

Engine size	Common examples in NZ	Kerb weight (kg)	Fuel consumption (l/100km)	CO_2-e emissions (g/km)
<1350cc	Honda Jazz 1.3S	1060	5.8	138[a]
1350–1599cc	Toyota Corolla 1.4D Diesel	1310	4.7	124
	Toyota Corolla 1.5 wagon	1170	6.4	153[b]
	Suzuki Swift 1.5XE	1040	6.3	150
	Suzuki Swift Sport 1.6	1090	7.5	179
	Ford Focus 1.6L	1241	6.7	159
	Honda Jazz Sport 1.5	1115	6.7	160[a]
1600–1999cc	Toyota Corolla 1.8GX Hatch	1300	7.3	171
	Toyota Corolla 2.0 Diesel	1435	5.4	140
	Ford Focus 1.8 Diesel	1426	5.3	139
	Ford Focus 2.0L Hatch	1339	8.0	189
	Ford Mondeo 2.0L Sedan	1477	7.9	189
	Ford Mondeo 2.0L Diesel	1578	7.1	189
	Mazda6 2.0 GLX	1412	7.7	183[a]
	Mazda3 2.0 GLX	1280	7.9	188[a]
2000–2999cc	Toyota Camry 2.4GL	1468	8.9	210
	Ford Focus 2.5L XR5	1437	9.3	224
	Ford Mondeo 2.3L	1543	9.3	223
	Ford Mondeo XR5 Turbo	1581	9.3	222
	Mazda6 2.5 Limited	1468	8.6	205[a]
	Mazda3 SP25	1351	8.6	205[a]
3000–3999cc	Holden Berlina 3.6	1709	10.6	252[a]
	Ford Falcon XT	1704	10.5	251
4000cc+	Holden Calais 6.0 V8	1826	12.9	307[a]
	Ford Falcon XR8	1825	14.0	334

a) For the vehicle manufacturers, the emissions figure was not quoted. The value shown has been calculated using the average conversion factor of the vehicles for which the data was provided; that is, 2.38kg CO_2-e per litre of petrol and 2.63kg CO_2-e per litre of diesel.

b) The figure quoted on the Toyota website was 135g/km. However, this is completely out of line with all the other petrol-powered vehicles, while 153 g/km is consistent with other vehicles. We have assumed this is a typographical error on the website.

The discussion so far has been limited to passenger cars. Light commercial vehicles are predominantly diesel powered and nearly 80% (by vehicle-kilometres travelled) of the fleet have engines between 2000cc and 2999cc. Approximately 9% have engines in the 1600–1999cc category, while 10% have engines over 3000cc. Generally, these vehicles are performing some form of freight task and when loaded, are likely to be significantly heavier than most passenger cars. It is also reasonable to assume that, as these vehicles are, by definition, commercial, the choice of vehicle configuration and engine size will be based primarily on economic efficiency. The opportunities for downsizing engines are likely to be limited. For example, the best-selling van in New Zealand over recent years has been the Toyota Hiace. This has two engine options: a 2.7l petrol engine or a 3.0l diesel engine. Thus the choice is between fuel types and there is no choice of engine size. Furthermore, Toyota does not offer any other vans. In the utility vehicle category, the best-selling vehicle in New Zealand is the Toyota Hilux. This is sold with the same two engine options as the Hiace van, with a 4.0l petrol engine as an additional alternative. The 4.0l petrol engine has a rated fuel consumption of 12.6l/100km, compared to 11.6l/100km for the 2.7l engine. Thus the fuel consumption and GHG emissions saving in downsizing the engine is 8%. However, as noted above, there are relatively few light commercial vehicles with the larger engine options, and even fewer with large petrol engines, so the potential savings from a whole-fleet perspective are very small.

7.5.3 Changing fuel type and/or engine technology

Comparing fuel efficiency between different fuel types is not straightforward. For example, a modern diesel-powered car may be up to 40% more fuel efficient (km/l) than an equivalent petrol-powered car, but the diesel fuel contains 11% more energy per litre than petrol. Thus part of the fuel-efficiency gain is owing to the higher energy content of the fuel, and part is owing to the greater efficiency of the diesel engine in extracting that energy. A kilogram of petrol has approximately the same energy content as a kilogram of diesel, and so if we measure fuel efficiency in km/kg we can isolate the effect of the improved efficiency of the diesel engine. However, this is not the case for other alternative fuels. For example, compared to petrol, LPG has a much lower energy content per litre of fuel, and a significantly higher energy content per kilogram of fuel.

The most widely used alternative fuel to petrol at present is diesel. Currently, diesel-powered cars are about 25–40% more fuel efficient than their petrol-powered equivalents, and this is improving. However, diesel fuel produces more GHG emissions per litre (by about 10–11%), and so the reduction in GHG emissions from using diesel fuel instead of petrol is about 17–33%.

Traditionally, diesel engines have been poorer performers with respect to air-quality (or 'regulated') emissions, particularly PM_{10} and NO_x. This is being addressed with increasingly stringent emissions standards. The Euro 5 emissions standards, which came into force in Europe in September 2009 for new models of car, specify the same allowable levels of PM_{10} emissions for petrol and diesel cars. A study undertaken by the European Union (Samaras et al 2005) found that diesel-powered vehicles fitted with particulate filters achieved similar levels of PM_{10} emissions to petrol-powered cars. PM_{10} emissions are considered the major cause of adverse human health effects in New Zealand (Fisher et al 2007). Euro 5 still allows diesel-powered cars to produce significantly more NO_x emissions than petrol-powered cars (180mg/km compared to 70mg/km). The Euro 6 limits, which are scheduled to come into effect in 2014, are more stringent with maximum allowable NO_x for diesel cars, at 80mg/km compared to 70mg/km for petrol. NO_x is a major contributor to smog and can cause respiratory and other health problems for susceptible people. On the other hand, petrol-powered cars produce significantly higher levels of HC emissions than diesel-powered cars. These emissions include benzene, toluene and xylene, all of which are known to have adverse health effects (Fisher et al 2007). HC emissions also contribute to smog. It is difficult to assess the extent to which the adverse effects of increased HC emissions for petrol cars match the adverse effects of increased NO_x from diesel cars. However, given that the main concern regarding adverse air-quality effects is in relation to PM_{10} emissions, it is reasonable to assume that diesel cars with particulate filters are approximately equivalent to petrol cars for air-quality emissions. This is not the case for diesel cars without particulate filters, and in the 'Cleaner drive' methodology, reported by Lane (2006) and illustrated in figure 7.1, the additional air-quality emissions from the diesel cars offset the reduced GHG emissions. Therefore, for smaller cars, petrol and diesel are approximately equivalent in terms of environmental impact.

It is worth noting that the US EPA emission standards make no distinction between petrol and diesel cars – they are both required to meet the same standards. However, there are relatively few diesel cars operating in the US. Currently, petrol-powered vehicles undertake just over 80% of the travel by light vehicles (see figure 6.8). If these were all converted to diesel power, there would be a reduction in the fleet's GHG emissions of 13–27%. This is the reduction in tailpipe emissions. According to the GREET 2.7 model, tailpipe emissions account for about 70% of the GHG emissions from a petrol-powered vehicle, with approximately 10% coming from the vehicle cycle and 20% from the fuel cycle. The reduction in GHG emissions from the fuel cycle is proportional to reduction in fuel consumption. There is very little difference in the vehicle cycle, so the potential reduction in overall GHG emissions is 12–26%.

As discussed in section 5.6.3, CNG and LPG can produce GHG emissions reductions of 20–30%, which is comparable with diesel. This is because these fuels have a higher proportion of hydrogen to carbon, and thus contain more energy per unit of carbon. CNG is slightly better than LPG, but the difference is small. These fuels both burn relatively cleanly and thus can meet air-quality emissions standards more easily than petrol or diesel. If all of the petrol-powered light vehicles were converted to LPG or CNG, the potential reduction in the fleet's GHG emissions would be about 16–24%. Again, this reduction refers to tailpipe emissions. With CNG and LPG vehicles, the fuel cycle emissions are also lower than for petrol, while the vehicle cycle is similar. The GREET model indicates an overall GHG emissions reduction of 15–16%.

Biofuels are used as a substitute, in whole or in part, for fossil fuels. Generally their GHG emissions performance is very similar to the fossil fuel they are replacing. In most cases, these fuels are cleaner-burning than the fossil fuels and thus can more easily meet air-quality emissions standards. Using biofuels leads to very little change in GHG emissions levels in the vehicle-operating component of life cycle emissions. The emission reductions occur in the fuel cycle component. The feedstock for biofuels is produced by plants or other organisms using solar energy and CO_2, and thus all of the CO_2 that is eventually emitted by the fuel into the atmosphere has previously been extracted from the atmosphere. However, the feedstock is not a ready-to-use fuel and energy is consumed in producing, harvesting, processing and distributing the biofuel, which also results in CO_2 emissions. The net emission reductions that can be achieved vary quite substantially, as previously shown in figure 5.1. In the worst cases these are negative, which effectively means that the GHG emissions generated from producing and distributing the biofuel are greater than the CO_2 extracted from the atmosphere by the crop. However, as long as measures are in place for ensuring that only appropriate biofuels are used, reductions in GHG emissions of 20–40% are achievable with 1st-generation biofuels. Second-generation biofuels should achieve emissions reductions of 80% or more.

Emissions reductions of these levels require the use of pure biofuels. In most countries, biofuels are initially blended with fossil fuels. New Zealand has legal provisions for biofuel blends to be sold for vehicle use: specifically, E10 and B5. E10 is a blend of 10% bioethanol and 90% petrol. If the bioethanol component comes from a source that produces a 20% reduction in GHG emissions, using the E10 fuel will produce a 2% reduction in GHG emissions. Similarly, B5 is a blend of 5% biodiesel and 95% petroleum diesel. Even if the whole light-vehicle fleet operated exclusively on biofuel blends, the GHG emission savings would be modest. The advent of 2nd-generation fuels would significantly increase the emission reductions, but they would still be relatively small. However, the development of a viable biofuels industry is likely to lead to high-proportion blends being used in the future. Second-generation biofuels used in high-proportion blends (E85, B100) would result in very substantial (80% or more) reductions in GHG emissions.

Synthetic fuels have generally been manufactured for strategic reasons, to overcome problems with the supply of petroleum-based fuels. At the vehicle operations level, many of them perform quite well, but they do not result in significant reductions in GHG emissions. In terms of the fuel cycle, the production of these fuels generally produces significant emissions and thus overall, the GHG emissions of these fuels are higher than those of the petroleum-based equivalents. Technology is being developed to capture the carbon produced during production, and to use waste heat for co-generation of electricity. If both of these technologies are applied, it is estimated that overall reductions in GHG emissions of between 25% and 50% are possible (Celik et al 2004, Gray and Tomlinson 1997). These estimates are based on the fuel cycle plus vehicle operations, but do not include the vehicle cycle. They are also based on fuel production technologies that are not yet operational.

Electric vehicles produce zero GHG emissions for the vehicle operations component, so it is important to consider both the fuel cycle and the vehicle cycle in these considerations. If we compare the environmental ratings given for electric cars shown in figure 7.1 (Lane 2006), we see that the ratings for cars using average generation-mix electricity were just over three times higher than the same cars using renewable electricity. This implies that two-thirds of the rating of the vehicles using average electricity was attributable to the fuel cycle, and one-third was attributable to the vehicle cycle. The average mix of electricity in the UK, on which Lane's calculations were based, had just over 70% of the electricity coming from thermal power stations, and more than half of these were coal fired. In New Zealand, only 30% of electricity is currently generated from thermal power stations and so the GHG emissions associated with the fuel cycle are significantly lower. Applying this to the 'Cleaner drive' ratings shown in figure 7.1, we would expect electric vehicles using average power generation in New Zealand to score ratings between 13.5 for a city car and 40 for an SUV; that is, less than half the environmental impact of a conventional petrol-driven car. If we use the GREET model, we find that the GHG emissions from the tailpipe are zero, those from the fuel cycle are about 20% higher than for petrol, while those for the vehicle cycle are 65–100% higher because of the emissions associated with the battery pack.

Combining these three components, we would expect the overall GHG emissions for an electric car using average electricity in New Zealand to be about 40–45% of those of an equivalent petrol car; that is, a reduction of 55–60%. These figures are for battery electric vehicles. Fuel cell electric vehicles do not save as much because, currently, the most efficient way to generate hydrogen is from natural gas, which produces more emissions than electricity generation in New Zealand. Using GREET model data, fuel cell electric vehicles produce about 40% fewer GHG emissions than the equivalent petrol car.

Hybrid vehicles are a compromise between vehicles powered by ICEs and battery electric vehicles. There are varying degrees of hybridisation. At the lowest level there are the so-called 'mild hybrids'. These vehicles have an up-rated alternator/starter motor that enables a number of fuel-saving measures to be implemented; specifically, stop/start operations and regenerative braking. In some cases, mild hybrids also provide some boost to the ICE in high power-demand situations. Mild hybrids typically produce fuel efficiency and GHG emissions savings of about 10–15% for vehicle operation and the fuel cycle. As only relatively minor vehicle technology changes are required, the increase in GHG emissions associated with the vehicle cycle is very small, and so the overall reduction in GHG emissions is about 9–13.5%

At the next level up, there is the fully grid-independent hybrid, such as the Toyota Prius. These vehicles can operate on electric power alone when the engine power demands are not excessive. They rely on the ICE to generate the electricity required to power the electric motor, and have moderate electric power storage capability. In the Greet model, the overall effect is a 25% reduction in GHG emissions. The reduction in fuel consumption, and hence tailpipe GHG emissions, is a little higher than this, but this is offset by a small increase in the vehicle-cycle emissions.

The final level is the full plug-in hybrid. These vehicles tend to have a larger battery pack and can be recharged by plugging into the electricity grid. This capability means that they can operate in electric-only mode for much greater distances than the grid-independent hybrids. Some plug-in hybrids are currently being produced on a small scale by modifying grid-independent hybrids, but at this time there are no plug-in hybrids available from the major vehicle manufacturers. Toyota is trialling a plug-in version of the Prius, and the Chevrolet Volt (also a plug-in) is due for release in 2010. The GHG emissions savings that can be achieved by a plug-in hybrid depend on the type of travel it is used for. If its daily travel demands are kept within the range of its battery pack, its GHG emissions performance will be comparable with a battery electric vehicle. If it is continuously used for long-distance travel, its GHG emissions will approach those of a grid-independent hybrid. The Chevrolet Volt is expected to have a range of 64km on full electric operation. The household travel data (see table 6.2) indicates that on any given day in the main urban areas, nearly 90% of cars travel less than this distance.

7.5.4 Vehicles from a lower fuel consumption/emissions category

As outlined earlier, we categorised vehicles into three groups relating broadly to their fuel consumption characteristics. These were, in order of increasing fuel-consumption and GHG emissions:

- human-powered vehicles and human-power hybrids
- low-powered vehicles
- standard vehicles.

Most of the travel undertaken in New Zealand uses vehicles from the third category, and all of the options we have discussed in the previous two sections are based on still using a vehicle from within that category, but with reduced fuel consumption and GHG emissions. In this section we review the gains that might be achieved by changing categories.

The first option is to change from a petrol-powered car to a low-powered vehicle. Lower-powered vehicles are primarily mopeds and quadricycles. Quadricycles, as a vehicle category, are not provided for under New Zealand regulations and they would currently be classified as cars (in Europe, quadricycles are not required to meet the same emissions and safety standards as normal cars). It is doubtful whether they could be operated legally in New Zealand.

In terms of fuel efficiency and GHG emissions, they should be compared with the smallest and most fuel-efficient cars currently available in New Zealand. In the 2008 AA Energywise Rally (Automobile Association 2008), the best-performing petrol car was a Mitsubishi Colt Plus, which achieved 4.8 l/100km. Its rated fuel economy on the standard drive cycle was 5.5 l/100km. The petrol car with the best-rated fuel efficiency was the Smart Fortwo, which was rated at 4.7 l/100km but actually achieved 5.0 l/100km. The most fuel-efficient vehicle overall was the diesel-powered Volkswagen Polo BlueMotion, which has a rated fuel efficiency of 3.8 l/100km, but actually achieved 3.6 l/100km. These values are comparable with the performance claimed for typical quadricycles (see section 3.4). Thus, if car users have already downsized to the smallest available cars, little or no additional reduction in fuel consumption or GHG emissions will result from changing to a quadricycle, particularly as the air-quality emissions are likely to be worse.

There is a case in favour of battery electric quadricycles and neighbourhood electric vehicles, because at present, they are more widely available than battery electric standard cars. The GHG emissions performance of these is superior to that of the electric standard cars because they are lighter and lower powered. The higher-powered mobility scooters would also fit into this category. GHG emissions savings would be around 70–80% of those of the smallest petrol cars.

Mopeds use about 25% of the fuel of the smallest cars (see section 3.3) and thus can produce GHG emissions reductions of more than 75% (the typical moped weighs less than 25% of the smallest cars and thus the vehicle cycle emissions will also decrease). Permissible air-quality emissions for mopeds are currently higher than those for cars, which gives the potential for some negative impacts in this regard. However, it is possible for mopeds to achieve more stringent emissions requirements, so this problem could be avoided. A range of electric-powered mopeds is also available, and it is possible to achieve very low GHG emissions with these.

It is difficult to quantify the GHG emissions performance of human-powered vehicles and hybrids, but it is very low. The fuel for human-powered vehicles is provided from food, which is essentially a biofuel. The human engine is relatively efficient, and the bicycle and its derivatives are very efficient. As noted in section 2.1, the energy required for a roadster bicycle at 24km/h is equivalent to 360km/l of petrol. If we assume the same GHG emissions reduction as for other 1st-generation biofuels (20–40%), then the GHG emissions from cycling are about 4–6 g/km of CO_2-e.

7.5.5 Summary

The previous three sections have reviewed the potential reduction in GHG emissions from three possible options for changing the vehicles used to undertake the transport task. To some degree these options are independent, and more than one can be applied with cumulative gains. For example, a large petrol-powered car can be replaced by a smaller car that is powered by LPG. This leads to gains from downsizing, and then further gains from changing fuel type. This is illustrated in table 7.2, which shows the well-to-wheels GHG emissions for various vehicle sizes and fuel technologies. These values were calculated using the GREET model, with the average fuel consumption data for New Zealand vehicles from table 7.1 and the average mix of electricity generation for New Zealand. The well-to-wheels analysis ignores the vehicle cycle emissions, which will be higher for the hybrid electric vehicles and the electric vehicles. The vehicle cycle GHG emissions for the electric vehicles could be as much as 10% of the petrol vehicle's emissions. If it is this high, the advantage of the hybrid electric vehicles over the diesel and LPG alternatives will be largely eroded. The battery electric vehicle will still have a significant GHG emissions advantage. It is interesting to note that if the US electricity generation mix is used instead of the New Zealand mix, the battery electric vehicle produces about the same GHG emissions as the hybrid vehicle. This is because over half of US electricity is generated using coal-fired stations, with a further 20% from other thermal stations.

Table 7.2 does not show all the options available, but it does illustrate the magnitude of the reductions in GHG emission and fuel consumption that would arise from various changes. For example, if a person who is currently driving a large petrol-powered car replaces it with a two-litre diesel-powered car, the GHG emissions will be reduced by over 200g/km of CO_2-e and fuel consumption will be more than halved. Replacing the two-litre diesel car with a bicycle would not achieve gains as large as this, even though it is a far more radical change.

Table 7.2 Well-to-wheels GHG emissions calculated using the GREET model

Vehicle	**Well-to-wheels GHG emissions (g/km CO_2-e)**				
	Petrol	**Diesel**	**LPG**	**Petrol–electric hybrid**	**Battery electric**
Car >4000cc	397	333	330	284	102
Car 3000–3999cc	306	258	257	219	80
Car 2000–2999cc	262	220	220	188	68
Car 1600–1999cc	223	188	187	160	58
Car 1350–1599cc	196	165	165	141	51
Car <1350cc	161	136	135	116	42
LCV 2000–2999cc	337	283	282	250	89
Moped	31				8

8 Vehicle selection drivers

8.1 Introduction

The drivers that influence vehicle selection are a complex mixture of subjective and objective factors. A rigorous analysis of these would be a major study in its own right and is beyond the scope of this work. Nevertheless, in order to develop policy recommendations for encouraging the use of more fuel-efficient, lower-emission vehicles, we must consider what the major vehicle selection drivers are. In discussing these, it is important to remember that the relative importance of the various drivers varies from person to person, and also depends on the transport task. Thus the same vehicle buyer may take a different perspective when purchasing a van for work purposes, compared to purchasing a car for personal transport. Furthermore, in many instances the factors will be based on perceptions rather than an evidence-based analysis.

Factors that affect vehicle choice include:

- size, capacity and vehicle type
- performance
- economics, including purchase price, operating costs and potential resale value
- safety
- fuel efficiency and environmental impacts
- status and image
- government policy.

8.2 Size, capacity and vehicle type

For many vehicle choices, these are fundamental factors. The vehicle must be large enough to undertake the required transport task, and of the appropriate configuration. Thus, for example, an electrician might require a large single-box van, while a builder might require a ute or small truck. However, in many cases there are options, and the choice is influenced by other factors. A family with three young children will require a vehicle with at least five seating positions and sufficient vehicle width to accommodate child seats and booster seats. In addition, they probably require a reasonably large luggage-carrying capacity. There are a number of vehicle types that can meet these requirements, including medium and large station wagons, people movers (MPVs) and sports utility vehicles (SUVs). Thus the final selection is driven by other considerations.

In some cases, the perceived size and capacity requirements are based on scenarios that rarely, if ever, occur. For example, it is not uncommon for families to have two cars that are each capable of transporting the whole family and its luggage, when both cars are never used simultaneously for this purpose. Their requirements could be fully met with one car of this size and one smaller car. Furthermore, having determined their size and capacity requirements, buyers then choose a vehicle that is larger than this.

In the case of light commercial vehicles we would expect that, in most cases, the size, capacity and vehicle type would be closely matched to the requirements of the transport task, and that there would be limited opportunities for downsizing. However, in the case of passenger vehicles, there will be opportunities for using smaller or more fuel-efficient vehicle types in many situations.

8.3 Performance

As noted in section 7.5.2, the open-road speed limit in New Zealand is currently 100km/h and the typical maximum grade on the state highway network is 10%. Many cars in New Zealand have substantially more power than is necessary to maintain 100km/h on a 10% grade when fully laden, and more power than is desirable for optimal fuel efficiency. This raises the question of why people choose these vehicles. Similarly, many people choose vehicles with four-wheel-drive (4WD) and advanced off-road capabilities, which have no benefit for on-highway operations and result in significant additional fuel consumption.

In some cases there will be occasional demands for higher levels of power and/or 4WD for some transport tasks (such as towing a boat or some other relatively heavy trailer), which will influence vehicle choice, but for many vehicles, the additional performance is unnecessary and unused.

It is not clear to what extent the over-performance is actively selected by the user, rather than being merely a side-effect of other features that are actively selected. For example, the user may select an SUV for its capacity and perceived safety advantages, rather than for its 4WD capabilities.

8.4 Economics

In theory, we might expect that economics would be the key driver in vehicle selection, provided the functional requirements of the transport task are met. This is probably true for light commercial vehicles, as the range of vehicles used for a particular transport task is usually relatively narrow, and they are all quite similar. However, in the case of passenger vehicles, it is much less obvious that this is so. For any given passenger transport task, the range of vehicles used is large and diverse. For example, the choice of vehicle for a family of two adults and two children might range from a 1600cc Japanese hatchback to a large European SUV. The ownership costs per kilometre of the European SUV are more than double those of the Japanese hatchback, so, in economic terms, there must be perceived benefits from the European SUV for which the person who selects it ahead of the Japanese hatchback is prepared to pay substantially.

This vehicle selection behaviour provides a useful indicator of the likely success of using pricing signals to encourage the use of more fuel-efficient, low-emitting vehicles. Carbon credits are currently worth about \$30 per tonne of CO_2-e internationally. Petrol produces approximately 2.38kg CO_2-e per litre and diesel produces 2.63kg CO_2-e per litre. If we embed the cost of carbon credits in the cost of fuel, petrol prices will rise by 7.1c per litre and diesel will rise by 7.9c per litre. If we include the cost of the emissions associated with the fuel cycle and the vehicle cycle, the increases will be about 10–11c per litre. Price increases of this magnitude are likely to have only a very minor effect on vehicle selection for the people currently choosing larger, less fuel-efficient vehicle options. On the other hand, these people are already prepared to spend quite a lot extra in vehicle costs for benefits that are primarily perceptual. With appropriate marketing, they may be the first to adopt fuel-efficient low-emissions vehicle technologies that are not justified on strictly economic terms.

8.5 Safety

The issue of safety for small, fuel-efficient cars is quite complicated. In the past, small cars did not achieve the same safety ratings as larger cars in crash testing. The reason for this is simple. Because the car is smaller, there is less space available for the ‘crumple’ zone, so the occupants are subjected to more severe decelerations, and it is more difficult to ensure that adequate space remains in the passenger compartment after the collision. The car manufacturers have put a lot of design and development effort into overcoming these difficulties, and many small cars now achieve the highest safety ratings possible in crash tests. However, the standard crash tests involve crashing the vehicle into a rigid barrier. This is physically equivalent to crashing into an identical vehicle travelling at the same speed in the opposite direction. In the real world, this type of crash may well involve hitting a much heavier vehicle. In this situation, the principle of conservation of momentum applies and the lighter vehicle will experience much higher deceleration, and hence impact force, than the heavy vehicle. Thus even if the occupant-protection systems in the two vehicles are equally good, the occupants of the lighter vehicle are more likely to suffer serious injury or death than the occupants of the heavier vehicle.

A statistical study undertaken in the Netherlands (Berends 2009) found that the relative weight difference between the vehicles in a two-car collision had a major impact on the crash outcome severity. Specifically, if an 800kg car was involved in a collision with an average-weight car (1079kg), the risk of a fatality in the lighter car was double what it would have been if two average-weight cars had collided. Moreover, the fatality risk in the heavier car was halved. Berends used these results to show that if the spread of weights in the vehicle fleet increases (as is currently happening in the Netherlands) then, with the same number of crashes, road fatalities will increase. Conversely, if all the vehicles in the fleet were the same weight, there would be a 25% reduction in road fatalities from two-car crashes.

A similar statistical analysis of the effect of vehicle weight on crash fatalities was undertaken by the National Highway Traffic Safety Administration in the US (Kahane 2003). This study considered the effect on the number of fatalities of reducing vehicle weight by 100lbs (45kg). Light trucks and cars were considered separately, and each of these was split into light and heavy categories based on the median weight. Seven crash modes were considered, which accounted for 96% of fatal crashes. A fatality was attributed to each vehicle involved in the crash, regardless of whether the victim was an occupant of that vehicle, or of the other vehicle, or a pedestrian or cyclist. Thus the fatality rate for the vehicle was a measure of both its crashworthiness (ability to protect its occupants) and its aggressivity (potential to cause harm to other road users). These two effects were not separated. In general, the reduction in weight caused an increase in the number of fatalities. The effect was greatest for the lighter car and least for the heavier light truck (for this vehicle, the size of the effect and uncertainty in the estimate is such that the effect could be zero). This is perhaps not too surprising, because the weight decrease considered was a fixed amount and thus was proportionately significantly greater for the smaller vehicle.

Kahane also looked at fatal crash rates per distance travelled, after adjusting for various confounding factors such age/gender, urban/rural, day/night and speed limit. The analysis considered 10 different vehicle types and sizes and seven crash modes. Where more than one vehicle was involved in a crash, the number of fatalities was divided by the number of vehicles and each was attributed a share. The results showed that, in general, the fatal-crash involvement rate reduced as vehicle weight increased. The one notable exception was for SUVs, where mid-size SUVs had a higher fatal-crash involvement rate than either small or large SUVs. Comparing vehicle types provided some interesting findings. Compact pickup trucks (average weight 1500kg) had about the same fatal-crash involvement rate as small cars (average weight 1100kg), while large pickup trucks (average weight 2000kg) had a similar fatal-crash involvement rate to mid-size cars (average weight 1400kg). Mid-size SUVs (average weight 1800kg) were about midway between small cars and very small cars (average weight 950kg). Thus, vehicle type was a major factor with pickup trucks and SUVs having fatal-crash rates comparable with much smaller, lighter cars. In part, this was owing to the increased aggressivity of these vehicles, but Kahane also analysed the driver fatality rates for these vehicles, which reflects crashworthiness. Although this did improve the relative safety of pickup trucks and SUVs, they still had fatality rates comparable with significantly lighter cars. The lowest fatality rate of any vehicle type was for minivans (people movers). It should be noted that this study was based on 1991–1999 model vehicles. Since then, there have been significant improvements in crashworthiness (particularly for small cars) and aggressivity (particularly relating to pedestrian impacts).

A number of statistical studies have also been undertaken using Australian and New Zealand crash data. The most recent is Newstead et al (2008). In this study, crashworthiness and aggressivity were determined separately for a large range of vehicle models manufactured between 1982 and 2006. The vehicles were classified into one of 10 market groups, for the purposes of presenting results. A summary of the results is reproduced in table 8.1. There were some differences between these results and Kahane's results for the US. In particular, people movers were among the best performers in the US but were relatively poor in Newstead's study, and large and medium SUVs received significantly better relative crashworthiness ratings in the latter study. Generally, there is a trend for crashworthiness to decrease with decreasing vehicle size, and aggressivity to increase with increasing vehicle size. The problem is that in selecting a vehicle, people are naturally more concerned with crashworthiness than aggressivity, and the more fuel-efficient vehicle types have poorer crashworthiness.

Newstead et al also considered the crashworthiness performance of individual makes and models. Among the 105 models with superior crashworthiness ratings, there were 15 small cars and 21 medium cars, but no light cars. The best-performing vehicle was, in fact, a small car. In terms of aggressivity, there were 83 models with superior performance, which included 18 light cars, 42 small cars and 17 medium cars. There were no medium or large 4WDs in this group. The age of the vehicles in this study spanned the 1982–2006 model years. As mentioned previously, there have been significant advances in crashworthiness performance in recent years, particularly for smaller cars. However, the absence of any light cars in the superior crashworthiness set is a concern when promoting the use of lighter, more fuel-efficient vehicles.

Table 8.1 Crashworthiness and aggressivity ratings (Newstead et al 2008)

Market group	Crashworthiness (serious-injury rate per 100 drivers involved)		Aggressivity (serious-injury rate per 100 drivers of other vehicles and unprotected road users involved)	
	Rating	Rank	Rating	Rank
Overall average	3.42		3.37	
Large 4WD	2.65	2	5.05	10
Medium 4WD	2.50	1	3.97	7
Compact 4WD	3.44	6	2.98	4
Commercial – van	3.66	7	4.24	9
Commercial – ute	3.25	4	3.99	8
People movers	3.80	8	3.64	6
Large cars	3.14	3	3.18	5
Medium cars	3.42	5	2.78	3
Small cars	3.97	9	2.43	2
Light cars	4.88	10	2.29	1

Safety is often mentioned as a major consideration in vehicle selection and is often used to justify the use of SUVs as family cars. The US data would suggest that this is based on a misconception, as SUVs do not perform as safely as cars, in terms of either crashworthiness or overall safety. However, the Australian and New Zealand data suggests that large and medium SUVs have good crashworthiness, but they achieve this at the expense of high aggressivity. Thus the users of SUVs impose additional safety risks on other road users in order to improve their own safety.

There are two main reasons for the difference in safety performance between smaller and larger vehicles. The first reason is that larger cars tend to be more expensive, and thus have additional and more advanced safety features built in. Furthermore, it is more difficult to achieve the same level of occupant protection when the vehicle is smaller and lighter. These issues are being addressed by vehicle manufacturers and this difference is being reduced.

The second reason is more fundamental. For the same vehicle speed, the heavier vehicle has more momentum. In a collision, momentum is conserved and thus the lighter vehicle experiences higher deceleration. The only way to reduce the momentum of the heavier vehicle is to slow it down. A vehicle with a laden weight of 2000kg would have to reduce its speed to 75km/h to have the same momentum as a car with a laden weight of 1500kg travelling at 100km/h.

However, the speed reduction would not need to be this large to be effective, for a number of reasons. Light vehicles are currently restricted to 100km/h on the open road, while heavy vehicles are limited to 90km/h. If the 90km/h limit were applied to all vehicles with a tare weight of more than, say, 1500kg, then the only people choosing to use larger, heavier vehicles would be those who actually need them. This would result in the fleet becoming more uniform in size which, as Berends (2009) showed, would reduce the severity of two-vehicle crashes. Furthermore, in two-car crashes involving one or more of the larger vehicles, the impact speeds would be substantially reduced. Lower travelling speeds give increased braking time, with the result that impact speeds decrease by much more than the reduction in travel speed.

The beneficial effect of reduced highway speed on safety is well established. During the 1970s oil crisis, a number of countries, including New Zealand and the US, reduced their open-road speed limits in order to conserve fuel. In New Zealand, the speed limit was reduced to 80km/h, and a reduction in road fatalities and injuries of more than 20% was recorded (Ministry of Transport 2008c). In the US, the speed limit was reduced to 55mph (88km/h), and this was credited with saving 2000–4000 lives per year (Godwin and Kulash 1988).

Reducing the speed limit for larger cars is unlikely to be a politically acceptable option. However, this issue of people choosing to use vehicles with better crashworthiness and higher aggressivity – that is, improving their own safety at the expense of that of other road users – is one that needs to be addressed.

8.6 Fuel efficiency and environmental impacts

To some degree, fuel efficiency is incorporated in the economics of running the vehicle, as discussed in section 8.4. However, there is also an element of sustainability and environmental concerns that motivates people to consider fuel efficiency and emissions performance when choosing a vehicle. For example, a number of film stars and other celebrities have chosen to drive a Toyota Prius. Clearly this choice is not for economic reasons although image, which we discuss in the next section, may be a factor.

The role of fuel efficiency in vehicle selection was investigated by Anable and Lane (2008). They reported on the well-established 'mpg paradox', where car buyers claim that fuel economy is a medium to high priority in selecting which vehicle to purchase, but their final decisions do not reflect this. Anable and Lane's study investigated whether this behaviour had changed with the increased public awareness of environmental issues and climate change, and with the rapid increases in fuel price that occurred in 2007–08. They found that there were some changes in behaviour, but that buyers were still not using actual fuel consumption as their main decision-making criterion. Rather, they were using crude surrogates, such as the cost of filling the tank or comparisons with their previous car, rather than comparisons with the best-in-class vehicles. Although this study was undertaken in the UK, there is no reason to believe New Zealanders would be different. In fact, because petrol is significantly cheaper in New Zealand, these factors may be less significant here.

8.7 Status and image

For many people, their car is far more than just a means of transport. It reflects their image of themselves and can be a symbol of status. This situation is exploited by car manufacturers, and their marketing often associates different vehicle models with various images of lifestyle and status. The high-rating television motoring show *Top gear* often discusses the image of a vehicle – that is, whether it is 'cool' or not – and what type of person would drive such a car.

To some extent this factor is the opposite of fuel economy. Many car buyers will claim that fuel economy is an important factor, and then make a decision that contradicts this assertion. Relatively few car buyers admit that image and status are a major factor in their decision-making process, and yet in many cases, this is the best explanation of the decision they made.

Although it is not easy to see how it would be done, improving the status and image of fuel-efficient vehicle options could significantly increase their uptake. One approach could be to extend the information provided on the websites www.rightcar.govt.nz and www.fuelsaver.govt.nz to actively promote a positive image for using safe, more fuel-efficient, smaller-engined vehicles.

8.8 Government policy

The effectiveness of government policy in encouraging the use of fuel-efficient, low-emission vehicles should not be underestimated. The government is a significant purchaser of new vehicles. It operates a fleet of more than 21,000 vehicles and purchases approximately 4000–4500 new vehicles per year (URS New Zealand Limited 2006). Total new light passenger vehicle sales in New Zealand are around 80,000 per year, so government purchases represent over 5%. The government's requirements for its new car purchases are expected to influence purchasing decisions of other fleet buyers, and eventually the general public (Office of the Minister for the Environment and Office of the Minister Responsible for Climate Change Issues 2006).

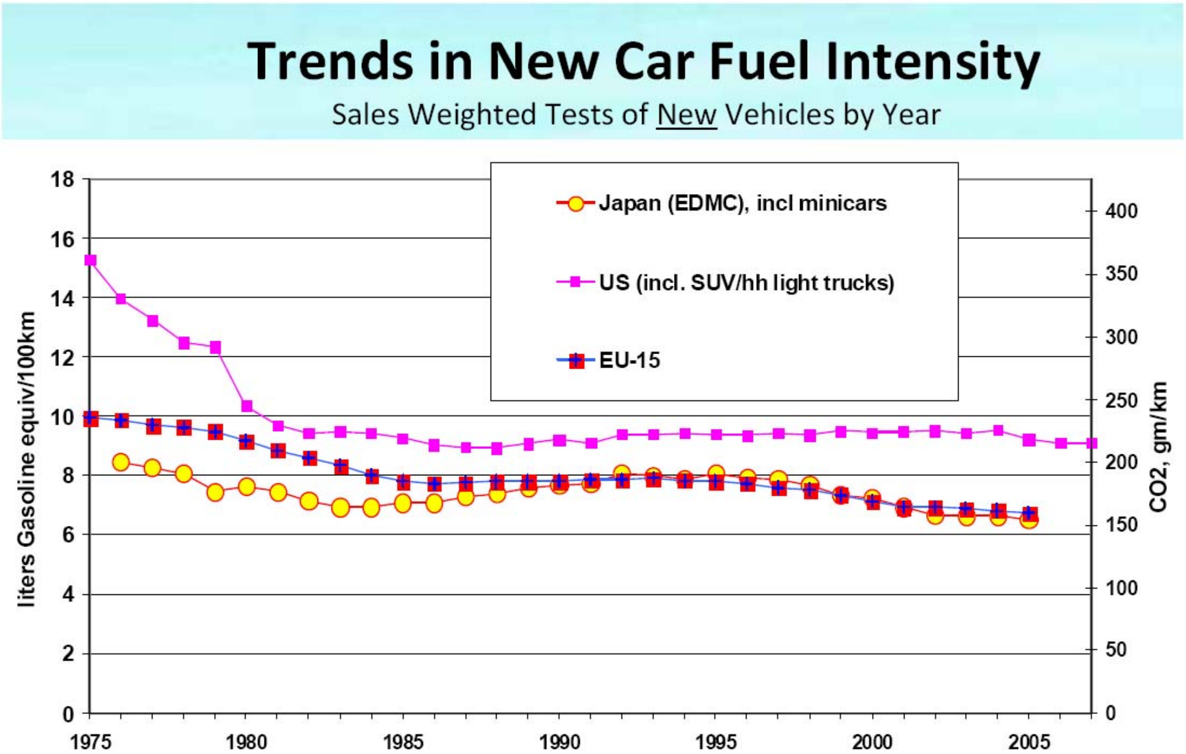
There is evidence for how this has been effective in the past. As outlined in section 5.6.3, in the late 1970s and early 1980s the government actively promoted the use of CNG and LPG. Most government cars were dual fuel, and New Zealand was a world leader in the uptake of this technology. In 1985 the government withdrew some of the incentives for CNG and LPG use, but more importantly, withdrew their support for the technology by no longer requiring government vehicles to use it. LPG and CNG continued to be subject to substantially lower fuel excise duty than petrol, and are still a sound economic choice for vehicles travelling high annual distances. However, for CNG in particular, the reduction in government support led to a decline in the number of suppliers offering conversion kits, as well as the number of refuelling facilities, and CNG light vehicles have virtually disappeared from the fleet. LPG has wider application than just as a vehicle fuel and has retained a presence in the fleet, but at a reduced level.

Similarly, the government's removal of the biofuels obligation in late 2008 has been cited as the reason for one international biodiesel producer abandoning plans to build a facility in New Zealand, and for a second producer halting their expansion plans (Rodrigues 2009). Subsequently, the government has introduced a grant programme to assist biodiesel producers with establishing facilities. This policy was announced in May 2009, so it is too soon to know whether it has been effective.

Care needs to taken in developing government policies to achieve particular goals, to avoid unintended outcomes. Following the oil crisis of the 1970s, both the US and Europe took steps to try to improve the fuel efficiency of their vehicle fleet so that their economies would be less vulnerable to oil price fluctuations, as described in section 4. The European approach has been to charge a relatively high tax on petrol to discourage use, and, in some countries, to incentivise alternative fuels, such as diesel and LPG.

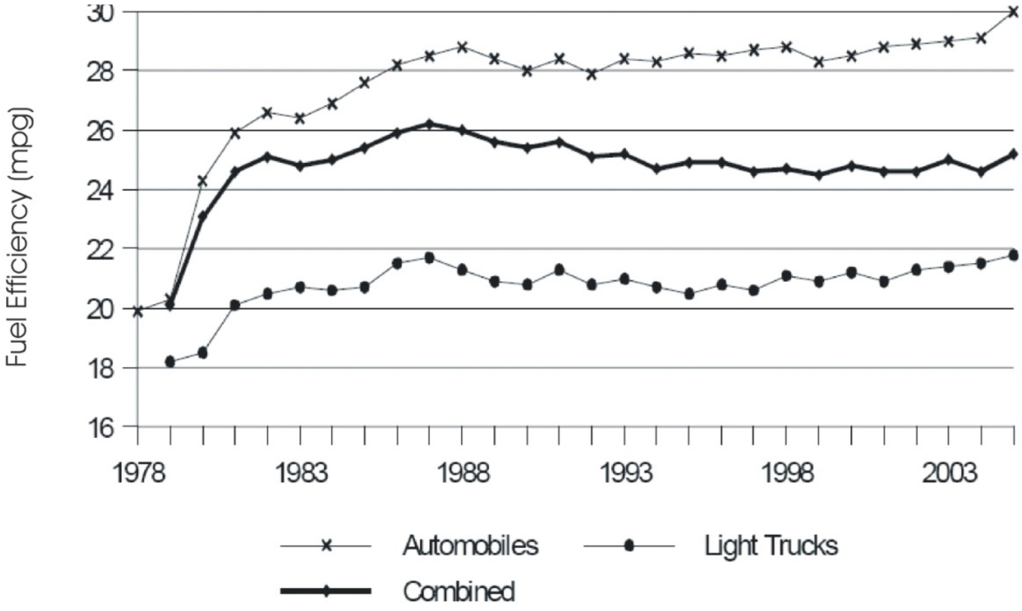
The US introduced the Corporate Average Fuel Efficiency (CAFE) standards. The CAFE standards required automobile manufacturers to achieve a specified average fuel efficiency over all of the vehicles they sold. The CAFE standards were set differently for cars and light trucks – cars were expected to more than halve their 1974 average fuel consumption by model year 1985, and light trucks were given a much less ambitious target – until model year 2004 – to achieve it (Committee on the Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards 2002). It would appear that the CAFE standards approach was initially very effective, as illustrated in figure 8.1 (Schipper 2008). However, between the early 1980s and 2006, there was effectively no reduction in fuel consumption in the US.

Figure 8.1 Weighted average fuel consumption (Schipper 2008)



When we look at the breakdown between cars and light trucks as shown in figure 8.2, which is reproduced from Yacobucci and Bamberger (2007), we see that the picture is more complex. Although the average fuel efficiency for both cars and light trucks improved between 1985 and 2005, the combined average did not. This is because there was a major swing away from station wagons, which are classified as cars, to minivans and SUVs, which are classified as light trucks. Thus, large station wagons, which have poor fuel efficiency for a car, were removed from the car fleet, improving its average performance. At the same time, minivans and SUVs, which have good fuel efficiency for a light truck, were added to the light truck fleet, improving its average performance. The overall effect was that the fuel-efficiency performance of the fleet as a whole deteriorated for most of the period.

Figure 8.2 Average fuel consumption for cars and light trucks (Yacobucci and Bamberger 2007)



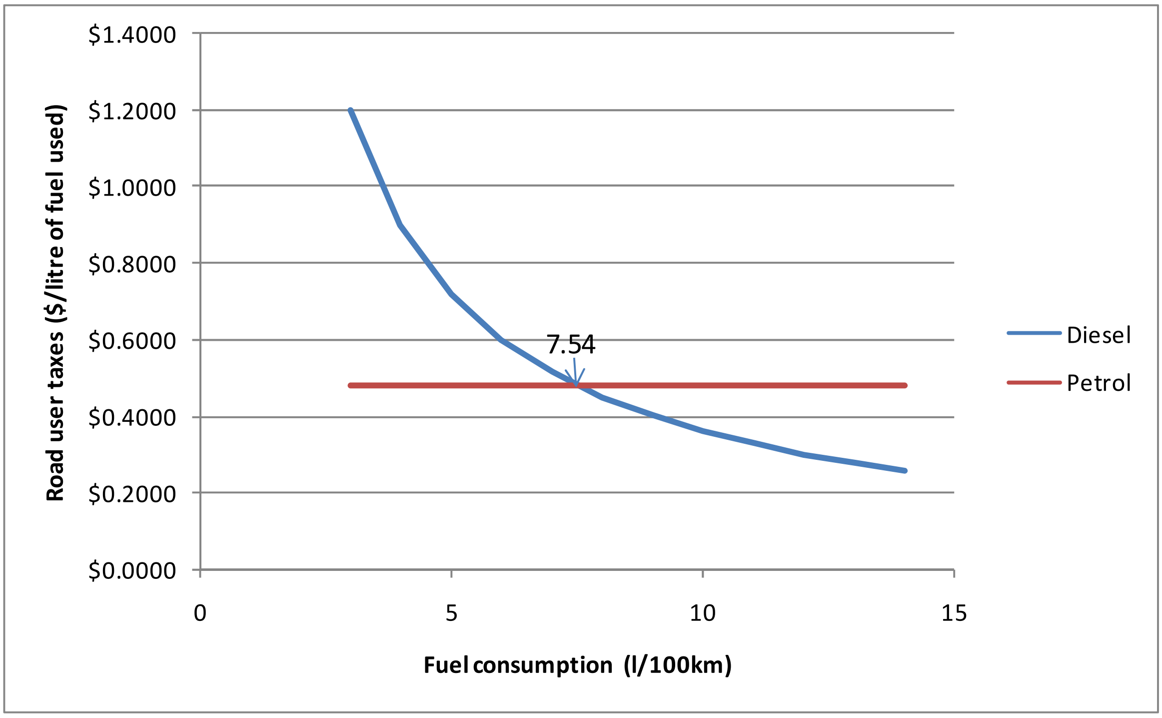
A similar unintended effect is occurring in New Zealand at present because of the way light vehicles are charged for their use of the road network:

- Diesel-powered vehicles are charged through a weight/distance-based schedule known as road user charges (RUCs).
- Petrol-powered vehicles are charged through a fuel excise duty (FED).

The RUC schedule was designed to recover the cost of road use from heavy vehicles so that road and rail could compete fairly. However, for light vehicles, the weight factor has almost no effect and RUCs are essentially a distance-based charge. Effectively, this means that the more fuel-efficient a diesel car is, the more tax per litre of fuel it pays. Thus small, fuel-efficient diesel-powered cars are disadvantaged relative to similar petrol-powered cars, while large, less fuel-efficient diesel cars (such as SUVs) are advantaged relative to their petrol-powered equivalents. This is illustrated in figure 8.3, which shows the equivalent FED rates for different fuel consumption levels at the current RUC rates. If the diesel vehicle’s average fuel consumption is 7.54l/100km, then RUCs gives the same FED per litre as petrol. If the fuel consumption is less than this, the diesel vehicle effectively pays a higher rate of FED, while if the fuel consumption is worse, the diesel vehicle pays a lower rate of FED.

It should be noted that RUCs were not designed to recover the externalities of environmental impacts, or to represent a form of carbon charge. The problem occurs because of the difference between the ways that RUCs are recovered from petrol and diesel vehicles. The FED on petrol provides an additional incentive for greater fuel efficiency, while the RUC on diesel does not. The Emissions Trading Scheme schedules oil companies to pay the costs of carbon emissions from liquid fossil fuels from 1 January 2011. This will add a cost to both fuels, and will provide an additional incentive for using more fuel-efficient vehicles.

Figure 8.3 Equivalent fuel excise duty (FED) for diesel cars at different fuel consumption rates



9 Summary of findings

The main aim of this research was to identify opportunities for reducing the emissions of New Zealand's light-vehicle fleet, to contribute to the government's goal of halving the country's 2007 per-capita greenhouse gas emissions by 2040. In this section, we summarise the main findings of the earlier sections.

Emissions can be categorised into two types:

- greenhouse gas (GHG) emissions, which are those that have been identified as contributing to climate change – usually measured in units of equivalent weight of carbon dioxide (CO_2-e)
- air-quality-related emissions, which are primarily those regulated by emission standards (hence, also called 'regulated emissions') – these emissions have adverse impacts on human health.

Most vehicle emissions fall into one or other of these categories with relatively little overlap, and so they can be considered independently.

This study has identified three broad categories of light vehicle with, in general, increasing rates of fuel consumption and GHG emissions. These are:

- human-powered and hybrid human-powered vehicles
- low-powered vehicles with restricted access to the road network
- standard vehicles with unrestricted access to the road network.

In general, the rules and regulations applying to these vehicles have evolved in response to the specifics of known vehicle types, rather than for generic categories. This means that for common vehicles such as cars and bicycles, the rules are typically quite well defined and clear, while for more unusual vehicle configurations such as skateboards and the Segway personal mobility device, there is often a degree of ambiguity and, in many cases, a lack of any rules.

9.1 Fuel and vehicle technologies

This report reviewed a number of the fuel and vehicle technologies that are currently available or are under development. The relative energy density of different fuels depends on whether this is determined on volumetric basis or a weight basis – that is, comparing fuel efficiency is complicated because the results depend on whether we consider km/l or km/kg of fuel. To simplify this, we used GHG emissions, which are measured in g/km of CO_2-e, as the basis for comparison. GHG emissions reflect the combined effect of the energy content of the fuel and the efficiency of the engine in using that fuel.

Our key findings are as follows:

- Diesel, LPG and CNG are all well-established fuels and can reduce GHG emissions at the tailpipe by about 20–30%, compared to petrol.
- Biofuels generate similar levels of GHG emissions at the tailpipe to the fuels they replace, but because the production of the feedstock used for making them removes CO_2 from the atmosphere, there is the potential for a net reduction in GHG emissions for the whole fuel cycle. For 1st-generation biofuels (those currently available) this net reduction ranges from -30% to 174% – that is, in the worst cases there is a net increase in emissions, while in the best cases there is a very substantial gain. For 2nd-generation biofuels (those currently under development) the GHG emissions reductions are expected to be around 80–90%, and the feedstock production will not compete for resources with food

production. These reductions in GHG emissions are based on fuels that consist of 100% biofuel. The current approach of using low-level biofuel blends, such as E10 and B5, has relatively little impact on overall GHG emissions, although it is a useful approach for getting the fuel technology established so that higher-level blends can be used in the future.

- Synthetic fuels, such as DME and Fischer-Tropsch diesel, also produce similar tailpipe GHG emissions to the fuel they replace. However, in general, the production process for these fuels also generates GHG emissions, so the overall effect is an increase in GHG emissions. Technologies are being developed to mitigate this effect, but they do not exist at present. There may be sound economic and strategic reasons for using these fuels, but at this point in time, they do not reduce GHG emissions.
- Hydrogen is essentially a carrier of energy, rather than a fuel in its own right. Some other form of fuel (electricity or natural gas) is used to generate the hydrogen, which is then subsequently converted back to energy for transport. Because of its low density, hydrogen needs to be either liquefied or compressed to very high pressures in order to be transported efficiently. The losses and emissions associated with the energy conversions and the transport and handling of the hydrogen mean that with current technology, it is better to use the fuel in its original form, rather than convert it to hydrogen.
- Mild hybrids, which use an up-rated starter motor and alternator to provide stop/start capability and regenerative braking (but do not have electric drive capability), can reduce GHG emissions by around 10% depending on the amount of congested urban driving.
- Fully grid-independent hybrids can reduce tailpipe GHG emissions by more than 40%. However, the additional electric drive capability and the large battery pack increase the emissions associated with the vehicle cycle. On a life-cycle basis, the reduction in GHG emissions is about 25%. The resulting emissions are slightly lower than those of diesel, LPG and CNG vehicles. Hybrid technology can be applied to diesel, LPG or CNG vehicles to produce greater GHG reductions.
- Battery electric vehicles produce the lowest GHG emissions. This is particularly so in New Zealand, where the average mix of power generation includes about 70% from renewable sources. On a whole-life-cycle basis, using average power, battery electric vehicles produce about 40–45% of the GHG emissions of a petrol equivalent. At the tailpipe, they produce zero emissions.
- Plug-in hybrids will have GHG emissions somewhere between those of grid-independent hybrids and battery electric vehicles, depending on use.
- Batteries are still a major constraint on electric vehicles in terms of weight, cost, energy density and recharge times. Hydrogen-based fuel cells provide an alternative to batteries, but as noted above, using hydrogen is less efficient than directly using the electricity. Other alternatives, such as ultracapacitors, are also being developed. These can withstand rapid recharging and thus offer the potential for ‘refuelling’ times that are comparable with petrol cars. However, their energy density is lower than batteries, and thus weight and range are still issues.
- There have, in the past, been significant differences in the air-quality emissions performance of these different fuel and engine technologies, but these are being managed through the requirements to comply with current emission standards. These standards are easier to achieve with some fuels. Other fuels require more sophisticated exhaust treatment systems, but all must comply.

9.2 Changing New Zealand's light-vehicle fleet

The vehicle registration data indicates that approximately 85% of New Zealand's light-vehicle fleet is petrol-powered and 15% is diesel-powered. In terms of annual distance travelled, approximately 80% is petrol-powered and 20% is diesel-powered. Eighty-seven percent of these vehicles are light passenger vehicles, and these undertake 85% of the distance travelled. The remainder are light commercial vehicles. Since 2000, there has been a trend towards larger-engined vehicles, and the annual distance travelled by these larger-engined vehicles has increased more than that for smaller-engined vehicles. The household travel survey (Ministry of Transport 2008b) showed that 76% of household trips, representing 94% of distance travelled, were undertaken by car or van. Clearly the biggest potential gains in fuel efficiency and GHG emissions performance can be achieved from petrol-powered light passenger vehicles.

There are three ways in which the fuel efficiency and GHG emissions performance of the light-vehicle fleet can be improved:

1. downsizing – using smaller-engined, lighter cars
2. changing fuel/engine technology to a more fuel-efficient, lower-emissions alternative
3. changing vehicle type to a more fuel-efficient category.

These three methods are not mutually exclusive. It is possible to both downsize and change fuel technology by, for example, replacing a large, petrol-powered car with a medium-sized hybrid car. There is considerable evidence to show that many people are using cars that have larger engines and weigh more than is necessary to meet their functional requirements.

- Downsizing:
  If all passenger-car drivers (except those currently driving vehicles in the smallest engine-size category) changed to a vehicle that was one engine-size category lower than their current vehicle, the reduction in GHG emissions and fuel consumption would be approximately 14%. In most cases, this change could be achieved without a significant loss of vehicle carrying capacity – for example, changing from a 6.0l V8 Holden Commodore to a 3.6l V6 Holden Commodore. If the change was to two engine-size categories down (for example, from a 4000cc+ car to a 2000–2999cc car, or from a 3000–3999cc car to a 1600–1999cc car), the potential reduction in GHG emissions is 22%. Light commercial vehicles are generally selected on a more strictly economic basis to match the requirements of the task, and thus have little scope for downsizing.

- Changing fuel/engine technology:
  As noted earlier, the currently available alternative fuels (diesel and LPG) provide GHG reductions of about 20%; petrol–electric hybrids generate GHG reductions of around 25% (including the additional emissions in the vehicle cycle because of having two drive systems and a battery pack); mild hybrids can produce GHG reductions of about 10% without the complexity of a full hybrid; and battery electric vehicles, which are just starting to appear on the market, can reduce GHG emissions by 55–60% (or more) if only renewable electricity is used. However, in the short term, the price and availability of these vehicles will limit their market penetration.

  Use of biofuels as low-level blends with conventional fuels (E10 and B5), can result in small total gains, depending on how and where they are produced. In the future, with 2nd-generation biofuels, and using high-level blends or pure biofuels, very substantial GHG reductions (80% or more) will be possible. Furthermore, as a largely agricultural country, New Zealand is well suited to developing an efficient domestic biofuel production capability.

- Changing vehicle type:
  Changing to a lower-emissions vehicle category is a bigger step for most drivers than downsizing, or changing fuel or engine technology. The potential reduction in GHG emissions is relatively large, but it is associated with a significant change in functional capability. For example, changing from a small car to a moped reduces GHG emissions by about 80%. The magnitude of the reduction is roughly comparable with that of changing from a large car (3000cc–4000cc) to a small car (<1350cc). In changing from a large car to a small car, the driver sacrifices some performance and some space, but retains the ability to carry passengers and luggage, and still has weather protection and full access to the entire road network. All of these functions are compromised when changing to a moped.

9.3 Factors influencing vehicle selection

In order to support the development of policies that would encourage the use of lower-emitting, more fuel-efficient vehicles, we reviewed the following seven main factors that influence vehicle selection:

- size, capacity and vehicle type
- performance
- economics
- safety
- fuel efficiency and environmental impacts
- status and image
- government policy.

These factors are inter-related and, to a degree, are based on the users' perceptions of them as much as the actual reality.

For most light commercial vehicles, economics is the primary factor – thus, the size and type of vehicle, engine performance, and fuel efficiency will be optimised for the particular transport task. Safety will be controlled by the vehicle meeting regulatory requirements while, in most cases, status and image will not be a factor. There are exceptions to this, where a company wishes to promote a particular image of itself and will choose its vehicles to reinforce this image. Government policy will be a factor if it indicates future directions that could have economic advantages.

For light passenger vehicles, the picture is much more complicated. Clearly, many people buy vehicles that are larger than they need, have capabilities that they never use, have performance far in excess of what can be used legally on New Zealand roads, and are not the most economic choice for their needs.

Safety is an important consideration in vehicle choice and, in general, larger vehicles are safer for their occupants. However, this safety is achieved at the expense of being less safe for other road users. Overall safety is enhanced if cars are more similar in size (Berends 2009). Also, although on average, larger cars are safer, a number of small cars in the New Zealand and Australian vehicle fleet came into the best-crashworthiness category in Newstead et al's 2008 research, and a number of large cars and large SUVs fell into the worst-crashworthiness category. Unfortunately, there were no very small cars among those with the best crashworthiness.

It has been found that while many car buyers state that fuel efficiency is an important consideration in their car-purchasing decision, their actual decision does not reflect this. With the recent volatility in fuel prices, there does appear to have been some change in this behaviour, although there is still a relatively poor understanding of fuel efficiency (Anable and Lane 2008).

A number of intangible factors influence a person's choice of vehicle and effectively override considerations of fuel efficiency and economics. We have simplistically called these factors 'status and image'. Some people will pay a significant premium price for these factors. Thus if the 'status and image' associated with fuel-efficient, low-emission vehicle options can be made appealing to this market segment, they will buy them, even if it is not economically sensible.

In the early 1980s government leadership influenced the uptake of fuel-efficient, low-emissions vehicles, with support for LPG and CNG vehicles. The economics of some of the alternative fuel options, such as biofuels, depend heavily on the world price of oil, which has been very volatile over the last two years. With the government's commitment to the use of biofuels, there was a guaranteed market for them in New Zealand, and at least two major international biofuel producers made plans to build plants in New Zealand. The government has now withdrawn the sales obligation for biofuels and these biofuel producers have cancelled their plans. There are government incentives in place for biofuel use, with bioethanol being exempt from fuel excise duty (42.5c per litre) and biodiesel receiving a capped grant of up to 42.5c per litre for fuel produced and used in New Zealand.

10 Recommendations

Based on our research, we make the following recommendations:

- Some older vehicle technologies that are fuel efficient and produce low GHG emissions also produce relatively high air-quality (or 'regulated') emissions. Specific cases are diesel-powered vehicles and two-stroke petrol engines. Vehicle emissions in New Zealand are regulated through the Vehicle Exhaust Emissions Rule 2007. This essentially requires most vehicles entering the country to meet one of four international sets of emissions standards. However, the New Zealand implementation dates for the level of standard (for example, Euro 4 versus Euro 3) lag behind those of the parent jurisdiction by some time. For example, the Euro 4 standard for passenger cars came into force in Europe in January 2005, but only applied in New Zealand from January 2008, while the implementation date for the Euro 5 standard, which came into force in Europe in September 2009, has not yet been set. Furthermore, no emissions standards apply to motorcycles or mopeds entering New Zealand, although standards do apply overseas. Encouraging technologies that meet the latest regulated emission standards would help the government meet the objective of reduced emissions. If incentives are used to increase the use of diesel, or of mopeds and motorcycles, they could target those with better emissions performance – this is done in Europe and Japan, where there are tax incentives for vehicles that out-perform the current emissions requirements.
- Compared to the fuel excise duty on petrol vehicles, the current RUC schedule effectively discourages small, fuel-efficient diesel cars and encourages large, less fuel-efficient diesel cars and SUVs. As a country, we have been importing relatively large numbers of used diesel SUVs with old-technology engines and relatively poor air-quality emissions, and relatively few new, small, diesel cars with the latest Euro 4 engines. This could be rectified by replacing RUCs with a fuel excise duty for light diesel vehicles. This would require a modification of the RUC schedule for heavy vehicles.
- Standard-sized electric vehicles are just beginning to enter the market. The government has offered an incentive in the form of an exemption from RUCs. Even so, at current pricing, the economics of battery electric vehicles is poor – although there will be some sales to early adopters of new technology. The distribution network for electricity is already in place, and in the short to medium term, no additional investment is needed to accommodate these vehicles. Over time, it is expected that the price will decrease and the economics of these vehicles will improve. In the short term, information on electric vehicles could be included on government consumer information websites to encourage interest.
- Smaller low-powered electric vehicles exist in significant numbers in other countries; for example, quadricycles in Europe, neighbourhood electric vehicles in the US, and higher-powered mobility scooters in Europe and elsewhere. At present, there is no provision for these vehicles to be used on New Zealand roads. We recommend a review regarding the potential role of these vehicles for lower-speed urban transport in New Zealand, and as a viable alternative to the car for older drivers. The review would need to include consideration of the safety features that these vehicles need, the speed limits and road access restrictions that should apply, and what the driver licence requirements should be, to establish a consistent set of principles for such vehicles.
- The government could investigate measures to encourage people to buy lighter cars with smaller engines, while still maintaining safety – with a particular focus on the current users of the larger vehicle categories. One approach could be to use the websites www.rightcar.govt.nz and www.fuelsaver.govt.nz to promote a positive image for using safe, more fuel-efficient, smaller-

engined vehicles. Reducing the range of vehicle sizes in the fleet would improve safety, and improved fuel efficiency would benefit the economy.

- In the longer term, biofuels will be able to produce substantial reductions in GHG emissions, using largely existing engine technologies with relatively minor modifications. New Zealand is well placed to become a significant biofuels producer and could, in the long term, become self-sufficient in transport fuel. This is something for the transport sector to pursue further.

11 References

An, F and A Sauer (2004) *Comparison of passenger vehicle fuel economy and greenhouse gas emission standards around the world*. Arlington: Pew Center on Global Climate Change. 33pp.

Anable, J and B Lane (2008) From ‘mpg paradox’to ‘mpg mirage’: How car purchasers are missing a trick when choosing new cars. *Low CVP Conference*, London.

Anon (2007a) *The ethanol fact book*. Washington DC: Clean Fuels Development Coalition.

Anon (2007b) Smart Fortwo Roadster is 'greenest car'. Whatcar? Accessed 31 August 2009. *www.whatcar.com/car-news/smart-fortwo-roadster-is-greenest-car-/228254*

Anon (2008) Mitsubishi iMiEV | Price at launch - $37.000. Accessed 14 September 2009. *http://green.autoblog.com/2008/07/14/mitsubishi-imiev-to-be-priced-around-37-000-at-launch/*

Anon (2009) MDI Enterprises S.A. - Air compressed cars - Flowair - Clean cars - Sustainable technology. Sébastien Braud. Accessed 14 September 2009. *www.mdi.lu/english/index.php*

Australian Bureau of Statistics (2008) 1301.0 - *Year book Australia, 2008.* Accessed 31 August 2009. *www.abs.gov.au/AUSSTATS/abs@.nsf/bb8db737e2af84b8ca2571780015701e/92D5907EC8B13B8ACA2573D2001062CB?opendocument*

Australian Bureau of Statistics (2009) *Motor vehicle census 9309.0.* Canberra: Australian Bureau of Statistics.

Automobile Association (2008) 2008 AA Energywise Rally winners announced. Accessed 31 August 2009. *www.aa.co.nz/about/events/AAenergywiserally/Pages/default.aspx*

Berends, EM (2009) De invloed van automassa op het letselrisico bij botsingen tussen twee personenauto's. *R-2009-5, SWOV*, Leidschendam.

Bossel, U, B Eliasson and G Taylor (2003) *The future of the hydrogen economy: Bright or bleak?*, Switzerland: ABB Switzerland Ltd, Corporate Research. 17pp.

Buschmann, G, H Clemens, M Hoetger and B Mayr (2001) The steam engine: Status of development and market potential. *MTZ Motortechnische Zeitschrift*: 1–17.

Celik, F, ED Larson, and RH Williams (2004) Transportation fuel from coal with low CO_2 emissions. *7th International Conference on Greenhouse Gas Control Technologies*, Vancouver, Canada.

Chan, CK, H Peng, G Liu, K McIlwrath, XF Zhang, RA Huggins and Y Cui (2008) High-performance lithium battery anodes using silicon nanowires. *Nature Nanotechnology* no. 3: 31–35.

CNW Marketing Research Inc (2006) *Dust to dust: The energy cost of new vehicles from concept to disposal*. Bandon, Oregon: CNW Research.

Committee on the Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards (2002) *Effectiveness and impact of corporate average fuel economy (CAFE) standards*. Washington DC: National Research Council.

Dalmia, S (2006) Have you hugged a Hummer today? Reason Foundation. Accessed on 31 August 2009. *www.reason.org/news/show/122517.html*

de Pont, J (2006) Enabling biofuels: Risks to vehicles and other engines. TERNZ report prepared for Ministry of Transport. Accessed on 11 November 2009. *www.transport.govt.nz/research/Documents/Vehicle-and-Engine-Risks-report-v3.1.pdf*

Demorro, C (2007) Prius outdoes Hummer in environmental damage. *The Recorder*, Central Connecticut State University.

Dempster, C (2000) The car that runs on air. BBC. Accessed 31 August 2009. *http://news.bbc.co.uk/2/hi/africa/988265.stm*

Dominion Post (2008) Flashback to LPG: The pros and cons of converting vehicles to gas. Accessed 31 August 2009. *www.stuff.co.nz/business/487977*

European Communities (2002) *Directive 2002/24/EC*. Brussels. 44pp.

Economic Commission for Europe Working Party on Road Traffic Safety (2001) Safety of skateboarders, in-line skaters, roller skaters, etc. Geneva: UN Economic Commision for Europe. Accessed 31 August 2009. *www.unece.org/trans/main/wp1/wp1doc/2001/wp12001-10e.pdf*

EECA (2009) Buying a vehicle. Accessed 31 August 2009. *www.energywise.govt.nz/how-to-be-energy-efficient/travelling-and-vehicles/buying-a-vehicle*

Energy Information and Modelling Group (2008) *New Zealand energy greenhouse gas report 1990–2007*. Wellington: Ministry of Economic Development. 39pp.

European Commission (2009) *EU energy and transport in figures: Statistical pocketbook 2009*. Brussels: Directorate General for Energy and Transport.

Fisher, G, T Kjellstrom, S Kingham, S Hales and R Shrestha (2007) *Health and air pollution in New Zealand.* Wellington: Health Research Council of New Zealand, Ministry for the Environment, Ministry of Transport.

Fletcher, G, P Nieuwenhuis and P Wells (2007) *Environmental rating for vehicles report*. Cardiff: CAIR-BRASS/Clifford Thames Ltd. 12pp.

Ford Motor Company (2009) Ford. Accessed 31 August 2009. *www.ford.co.nz/*

Fraser, J (2006) EEStor ultracapacitor shuns publicity. Accessed 31 August 2009. *http://thefraserdomain.typepad.com/energy/2006/01/eestor_ultracap.html*

Fung, D (2009) Mitsubishi i MiEV. Accessed 31 August 2009. *www.cnet.com.au/mitsubishi-i-miev-339295540.htm*

Gallagher, E (2008) *The Gallagher review of the indirect effects of biofuels production*. St Leonards-on-Sea: Renewable Fuels Agency. 92pp.

Gleick, PH (2007) *Hummer versus Prius: "Dust to Dust" report misleads the media and public with bad science.* Oakland, Ca: Pacific Institute. 7pp.

Godwin, SR and DJ Kulash (1988) The 55 mph speed limit on US roads: issues involved. *Transport Reviews 8*, no.3: 219–235.

Goodall, N (2009) Biofuels in the UK. *EECA Biofuels & Electric Vehicles Conference*, Wellington.

Gray, D and G Tomlinson (1997) Efficient and environmentally sound use of our domestic coal and natural gas resources. *Energeia 8*, no.4: 1–6.

Greene, DL and A Schafer (2003) *Reducing greenhouse gas emissions from U.S. transportation*. Pew Center on Global Climate Change, Arlington, Va.

Hauenstein, H and L Schewel (2007) *Checking Dust to Dust's assumptions about the Prius and the Hummer*: Fact-checking using the GREET life cycle model underlines the deep divide between the Dust to Dust study and all previous scientific work. Boulder, Co: Rocky Mountain Institute.

Holden (2009) Holden innovation – EcoLine – LPG. Accessed 31 August 2009. *www.holden.co.nz/innovation/lpg.html*

Honda (2009a) Honda cars: New and certified used cars from American Honda. Accessed 31 August 2009. *http://automobiles.honda.com/tools/shopping.aspx?Function=new_lease_calculator*

Honda (2009b) Honda FCX Clarity: hydrogen fuel cell vehicle. Accessed 31 August 2009. *http://automobiles.honda.com/fcx-clarity/*

Jeuland, N, X Montagne and X Gautrot (2004) Potentiality of ethanol as a fuel for dedicated engine. *Oil & Gas Science and Technology – Rev. IFP 59*, no.6: 559–570.

Joseph, H (2009) Moving to high biofuel blends: the Brazilian experience. *EECA Biofuels & Electric Vehicles Conference 2009*, Wellington.

Kahane, CJ (2003) Vehicle weight, fatality risk and crash compatibility of model year 1991–99 passenger cars and light trucks. *DOT HS 809 662*, Washington DC: National Highway Traffic Safety Administration.

Kassakian, J, J Schindall and R Signorelli (2006) Carbon nanotube enhanced ultracapacitors. Accessed 31 August 2009. *http://lees.mit.edu/lees/ultracapacitors.htm*

Lamy, V (2002) Assessment of low-speed electric vehicles in urban communities: Pilot project. *Transport Canada TP 13942E*. 59pp.

Lane, B (2006) Life cycle assessment of vehicle fuels and technologies. London: Borough of Camden. 69pp.

Limbaugh, R (2007) Prius worse for the earth than the Hummer! Rush 24/7. Accessed 28 October 2009. Transcript on *http://radioequalizer.blogspot.com/2007/07/prius-owners-bay-area-liberals-rush.html*

MacLean, HL and LB Lave (2000) Environmental implications of alternative fuelled automobiles: Air quality and greenhouse gas tradeoffs. *Environmental Science and Technology 34*, no.2: 225–31.

Ministry of Transport (2008a) *The New Zealand transport strategy*. Wellington: Ministry of Transport.

Ministry of Transport (2008b) Ongoing New Zealand household travel survey 2003–07. Accessed 14 September 2009. *www.transport.govt.nz/research/Documents/Ongoing NZ Household Travel Survey_Regions to 2008.xls*

Ministry of Transport (2008c) *Motor vehicle crashes in New Zealand 2007*. Wellington: Ministry of Transport.

Ministry of Transport (2008d) New Zealand vehicle fleet statistics. Accessed 14 September 2009. *www.transport.govt.nz/research/Documents/NZ Vehicle Fleet Graphs 2008.xls*

Mößbauer, S, F Durst, D Trimis and T Haas (2001) Zero emission engine: a novel steam engine for automotive applications. *Proceedings The 5th International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines (COMBURA 2001)*, Nagoya, Japan: 473–8.

NZ Transport Agency (2009) *New Zealand motor vehicle registration statistics 2008*. Palmerston North: NZ Transport Agency. 67pp.

Newstead, S, L Watson and M Cameron (2008) Vehicle safety ratings estimated from police reported crash data: 2008 update Australian and New Zealand crashes during 1987–2006. *MUARC report no.280*, Melbourne.

OECD (2009) *OECD Factbook 2009: Economic, environmental and social statistics*. Paris: OECD.

Office of the Minister for the Environment, and Office of the Minister Responsible for Climate Change Issues (2006) *Government leadership in energy efficiency and climate change through the Govt[3] programme.* Wellington: Cabinet Policy Committee.

Pew Center on Global Climate Change (2004) Comparison of passenger vehicle fuel economy and greenhouse gas emission standards around the world. Accessed 14 September 2009. *www.pewclimate.org/docUploads/Fuel Economy and GHG Standards_010605_110719.pdf*

Platell, O (1976) Progress of Saab Scania's steam power project. *SAE Paper 760344*.SAE, Warrendale, Pa.

Police Service of Northern Ireland (2006) PSNI to get tough with 'Go-Ped' users. Accessed 25 August 2008. *www.psni.police.uk/index/media_centre/press_releases/pg_press_releases_2006/pr_2006_may/_psni_to_get_tough_with__go-ped__users_29_05_06.htm*

Pucher, J (2002) Renaissance of public transport in the United States? *Transportation Quarterly 56*, no.1: 33–49.

Pucher, J and R Buehler (2008) Making cycling irresistible: lessons from The Netherlands, Denmark and Germany. *Transport Reviews 28*, no.4: 495–528.

Reed, J (2007) Prius loses ground to petrol cars. *Financial Times*, London.

Reguly, E (2007) Rethinking green. *Globe and Mail*, Toronto.

Rodrigues, S (2009) Government grants life-line to biodiesel industry. *National Business Review*, Wellington.

Ryan (2008) Saab history: the nine cylinder Saab steam engine. Accessed 31 August 2009. *www.saabhistory.com/2008/04/04/the-nine-cylinder-saab-steam-engine/*

Samaras, Z, L Ntziachristos, N Thompson, D Hall, R Westerholm and P Boulter (2005) Characterisation of exhaust particulate emissions from road vehicles (PARTICULATES). Brussels: European Commission – DG TrEn. 79pp.

Sawyer, CA (2001) Clean & 'Ezee'. Automotive Design and Production. Accessed 31 August 2009. *www.autofieldguide.com/articles/070102.html*

Saxe, H (2003) An environmental and economic assessment of mopeds in Denmark. *International Journal of Environmental Technology and Management 3*, no.3/4: 349–67.

Schipper, L (2008) Automobile fuel economy and CO_2 emissions in industrialized countries: troubling trends through 2005–2006. *TRB 88th Annual Meeting*, Washington DC.

Simpson, A (2004) Full cycle assessment of alternative fuels for light duty road vehicles in Australia. *19th World Energy Congress*, Sydney.

Statistics New Zealand (2008) *New Zealand official yearbook 2008*. North Shore City: David Bateman.

Sullivan, M (2007) World's first air-powered car: zero emissions by next summer. *Popular Mechanics*. Accessed 31 August 2009. *www.popularmechanics.com/automotive/new_cars/4217016.html?series=19*

Templeton, B (2008) Is green U.S. mass transit a big myth? Accessed 31 August 2009. *www.templetons.com/brad/transit-myth.html*

Toyota USA (2009) Toyota cars, trucks, SUVs & accessories. Accessed 31 August 2009. *www.toyota.com*

UrbanScooters.com (2003) Motorized scooter, electric bike and pocket bike laws. Accessed 25 August 2008. *http://urbanscooters.com/cgi-bin/urbanscooters/electric-scooters-scooter-laws.html*

URS New Zealand Limited (2006) *Current government fleet and procurement practice*. Wellington: Ministry for the Environment and Ministry of Transport. 113pp.

van Vliet, O, A Faaij and W Turkenburg (2007) Developments in Fischer-Tropsch diesel in a WTW chain perspective. *International Conference on Transport and Environment*, Milan.

Wang, M, A Burnham and Y Wu (2007) Greenhouse gases, regulated emissions, and energy use in transportation (GREET). Argonne, Illinois: Argonne National Laboratory.

Whitt, FR and DG Wilson (1982) *Bicycling science*. Boston: The Massachusetts Institute of Technology.

Will, GF (2007) Fuzzy climate math. *Washington Post*, Washington DC, A27.

Yacobucci, BD and R Bamberger (2007) *Automobile and light truck fuel economy: the CAFE standards*. Washington DC: Congressional Research Service. 17pp.

11.1 Sources of photographs

Accessed October 2009.

Figure 2.1 A Dutch 'bakfiets': *http://en.wikipedia.org/wiki/File:WorkCycles-Cargobike-delivery.JPG*

Figure 2.2 Lightning P383 short wheelbase recumbent: *http://en.wikipedia.org/wiki/File:Lightning_P38_RideXNC.jpg*

Figure 2.3 Easyracer long wheelbase recumbent: J de Pont

Figure 2.4 Long wheelbase recumbent with fairing: *http://en.wikipedia.org/wiki/File:V2fairing2.jpg*

Figure 2.5 Recumbent tricycle with fairing: *http://en.wikipedia.org/wiki/File:Faireds1.jpg*

Figure 2.6 Alleweder KV4 velomobile: *http://upload.wikimedia.org/wikipedia/commons/8/88/Leeinvelo1.JPG*

Figure 2.7 Flevobike Versatile velomobiles: *www.ligfietsshop.nl/images/stories/flevobike_versatile.jpg*

Figure 2.8 Current model VeloSolex 4800S: *commons.wikimedia.org/wiki/File:Velosolex.jpg*

Figure 2.9 1967 Honda P50 moped: *www.vintagebike.co.uk/.../images/Honda-P50-2.jpg*

Figure 2.10 Redmax engine kit: *www.bikeengines.com/picpage.htm*

Figure 2.11 Rotary Australia engine kit: *www.rotarybike.com/uploads/raleigh%20lrge.jpg*

Figure 2.12 Aerorider hybrid electric velomobile: *www.vkblog.nl/pub/mm/tempest/173/Image/techniek/aerorider.jpg*

Figure 2.13 Twike two-seater hybrid: *www.ubergizmo.com/photos/2006/9/twike_large.jpg*

Figure 3.1 Three-wheeled mobility scooter: *http://electricscootershome.com/tag/electric-mobility-scooters/*

Figure 3.2 Four-wheeled mobility scooter:
www.easymobilityco.com/images/merits_scooters/S341_475.jpg

Figure 3.3 Segway personal transportation device: *http://commons.wikimedia.org/wiki/File:Segway.JPG*

Figure 3.4 Chatenet S2 light quadricycle: *www.automobiles-chatenet.com/fr/bs2.php*

Figure 3.5 Chatenet Speedino standard quadricycle: *www.qdoscars.co.uk/chatenex.htm*

Figure 3.6 Aixam-Mega City electric quadricycle:
http://commons.wikimedia.org/wiki/File:Aixam_Mega.JPG

Figure 3.7 Reva G-Wiz electric quadricycle:
http://en.wikipedia.org/wiki/File:G-Wiz_-2_28_07_2007_(932064472).jpg

Figure 3.8 Road-legal quadricycle: *http://shop.ramquads.com/product2020216catno20216.html*

Figure 3.9 Mega Multitruck quadricycle: *http://en.wikipedia.org/wiki/File:Mega_MultiTruck.jpg*

Figure 3.10 Aixam hit from behind by an Audi A6 travelling at 100km/h:
www.rijnders-minicars.nl/Ongeval.php

Figure 3.11 Examples of US neighbourhood electric vehicles:
http://en.wikipedia.org/wiki/File:NEV-iT-BlueSedan-RFQ0254.JPG
http://en.wikipedia.org/wiki/File:NEV-BlueZENN-RSFQ0244.JPG
http://en.wikipedia.org/wiki/File:LD_250408_23_4_S_Front.jpg
www.westerngolfcar.com/lidocoupe.htm

Figure 3.12 A range of kei cars:
http://en.wikipedia.org/wiki/File:Daihatsu_Mira2006.JPG
http://motorfetish.files.wordpress.com/2009/04/suzuki-cappuccino-f3q-a-943.jpg
http://en.wikipedia.org/wiki/File:Suzuki_Wagonr_2003.jpg
http://en.wikipedia.org/wiki/File:Daihatsu_Hijet_Climber_001.JPG

Figure 4.4 1886 Benz Motorwagen: *http://en.wikipedia.org/wiki/File:1885Benz.jpg*

Figure 4.5 1932 Morgan Super Sports Aero: *http://en.wikipedia.org/wiki/File:Morgan_3-Wheeler_193X.jpg*

Figure 4.6 1950s Messerschmitt KR200: *http://en.wikipedia.org/wiki/File:Messerschmitt_Kabinenroller.jpg*

Figure 4.7 1999 Reliant Robin:
http://de.wikipedia.org/w/index.php?title=Datei:Reliant_Robin_Green.jpg&filetimestamp=20070319135846

Figure 4.8 2007 Modified Harley Davidson trike:
http://commons.wikimedia.org/wiki/File:Harley.trike.750pix.jpg

Figure 4.9 Sri Lankan tuk-tuk: *http://en.wikipedia.org/wiki/File:Sri_Lanka_Tuk_Tuk.jpg*

Figure 4.10 2007 Carver One: *http://en.wikipedia.org/wiki/File:Carver_one_06011701.jpg*

Figure 4.11 2008 prototype Aptera Typ-1:
http://commons.wikimedia.org/wiki/File:Aptera_Typ-1_Wallpaper.jpg

Figure 4.12 1931 Austin Seven four-seater saloon:
http://en.wikipedia.org/wiki/File:Austin_Seven_Saloon_1931.jpg

Figure 4.13 1930 Austin Seven Ulster two-seater sports car:
http://commons.wikimedia.org/wiki/File:Austin_Seven_Ulster_2-Seater_Sports_1930.jpg

Figure 4.14 A selection of light, small-engined vehicles of the 1950s and 60s:
www.microcarmuseum.com/tour/atlas.html
www.microcarmuseum.com/tour/lloyd.html
www.microcarmuseum.com/tour/lloyd-alexander.html
www.microcarmuseum.com/tour/isetta-1960.html
www.microcarmuseum.com/tour/bmw600.html
www.microcarmuseum.com/tour/nsu-prinz-rhd.html
www.microcarmuseum.com/tour/goggo-dart.html
www.microcarmuseum.com/tour/goggo-t300sunroof.html
www.microcarmuseum.com/tour/trabant.html
www.microcarmuseum.com/tour/zeta.html
www.microcarmuseum.com/tour/subaru360.html
www.microcarmuseum.com/tour/mazda-r360.html

Figure 4.18 Modern fuel-efficient vehicles:
http://en.wikipedia.org/wiki/File:2008_Smart_ForTwo_Passion_Coupe.jpg
www.automobilesreview.com/gallery/toyota-iq/toyota-iq-01.html
http://upload.wikimedia.org/wikipedia/commons/0/09/Audi_A2_L_Silber.jpg
http://upload.wikimedia.org/wikipedia/commons/2/26/Toyota_Aygo_front.JPG
http://en.wikipedia.org/wiki/File:VW_Polo_Blue_Motion.jpg
http://zh-min-nan.wikipedia.org/wiki/File:Volkswagen-1-Litre-'02.jpg

Figure 4.19 Examples of steam cars:
www.stanleymotorcarriage.com/
http://en.wikipedia.org/wiki/File:1924Stanley740-boiler.jpg
www.stanleysteamers.com/photoalbum/patpix/stan-lucas'-doble-last-e-series-built.jpg
www.damninteresting.net/content/doble_boiler_large.jpg

Figure 4.20 1911 Baker ‘V’ extension front coupe:
www.conceptcarz.com/vehicle/z11282/1911-Baker-Electric.aspx

Figure 4.21 Selection of electric cars of the 1990s:
http://jetube.wordpress.com/2009/08/
http://en.wikipedia.org/wiki/File:GSFRFrontQuarterView.jpg
www.aa1car.com/library/Ford_Think.htm
http://en.wikipedia.org/wiki/File:Toyota_RAV4_EV--DC.jpg
www.electroauto.cz/106saxo_electrique.html
http://upload.wikimedia.org/wikipedia/commons/b/b0/Elcidislarochelle.jpg

Figure 4.22 Selection of upcoming electric vehicles:
www.channel4.com/4car/media/features/2006/who-killed-the-electric-car/03-large/who-tesla-electric-car.jpg
http://upload.wikimedia.org/wikipedia/commons/d/de/Think_City_2007.jpg
www.theweeklydriver.com/news?Page=3
www.treehugger.com/files/2007/01/the_buzz_around.php

Figure 4.23 UK electric milk float:
http://en.wikipedia.org/wiki/File:Dairy_Crest_Ex_Unigate_Wales_And_Edwards_Rangemaster_Milk_Float.jpg

Figure 4.24 Smith Edison electric delivery van: *www.greencarsite.co.uk/GREENNEWS/smith-ev-europe.htm*

12 Acronyms and abbreviations

CAFE	Corporate Average Fuel Economy standards
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2-e	carbon dioxide equivalent
DME	dimethyl ether
EESU	electrical energy storage unit
EPA	environmental protection agency
FAME	fatty-acid methyl ester
FED	fuel excise duty
FT	Fischer-Tropsch – a process for creating synthetic diesel fuel
4WD	four-wheel-drive
GHG	greenhouse gas
HC	hydrocarbon
HPV	human-powered vehicle
ICE	internal combustion engine
Li-ion	lithium-ion
LNG	liquid natural gas
LPG	liquefied petroleum gas
LSV	low-speed vehicle
MPV	multi-purpose vehicle (people mover)
NERD	non-esterified renewable diesel
NEV	neighbourhood electric vehicle
Ni-Cd	nickel-cadmium
NiMH	nickel metal hydride
NMVOCs	non-methane volatile organic compounds
NO_x	oxides of nitrogen
NZTA	New Zealand Transport Agency
PM_{10}	particulate matter with particle sizes greater than 10µm
RUC	road user charges
SUV	sports utility vehicle