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making cars more fuel efficient

Technology for Real Improvements on the Road

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FOREWORD AND ACKNOWLEDGEMENTS

This report provides a technical analysis of why vehicles perform better in fuel economy test procedures than they do in actual operation on the road. It examines how the gap between test and "on-road" emissions can be closed. A variety of technologies are examined that, whilst they show now gains in the tests used to certify vehicles for sale, could improve fuel economy and reduce CO_2 emissions in the real world. Manufacturers have little or no incentive to introduce these technologies although they could be used to cut emissions by over 10%. The practical information presented here should assist policy makers in identifying technologies and other strategies such as driver training to promote fuel efficiency on the roads and provide incentives for the uptake of the relevant technologies.

This book was produced jointly by the European Conference of Ministers of Transport and the International Energy Agency, Office of Energy Technology and R&D. The ECMT and IEA would like to thank Mr. K. G. Duleep of EEA, Arlington, Virginia for providing the main analysis underlying this report. We would also like to thank Novem, the Dutch energy agency for important contributions in the area of efficient driving behaviour. Useful comments were received from many individuals, including Tom Howes (European Commission, DG-TREN), Dan Santini (Argonne National Laboratory, US), and Feng An (independent consultant). Of course any errors or omissions remain the responsibility of ECMT and IEA.

TABLE OF CONTENTS

EXECUTIVE SUMMARY 9

Literature Review 10
Technologies to Reduce Shortfall 11
Technology Cost-effectiveness 12
Policies to Promote Technology Introduction 18

1. INTRODUCTION 21

2. LITERATURE REVIEW OF “SHORTFALL” 23

Mix of Driving Environments 24
Road Conditions/Topography 24
Vehicle Accessories and Cargo 25
Vehicle Technology-Specific Effects 25

3. THE EFFECT OF AMBIENT CONDITIONS, VEHICLE MAINTENANCE AND DRIVER BEHAVIOUR ON FUEL ECONOMY 31

The Effect of Ambient Conditions on Fuel Economy 31
The Influence of Vehicle Maintenance on Fuel Economy 31
The Importance of Driver Behaviour for Fuel Economy 33

4. DRIVING CYCLES AND SHORTFALL DATA 37

5. TECHNOLOGIES TO IMPROVE FUEL ECONOMY OF GASOLINE VEHICLES 29

Engine Technologies 45
Transmission Technologies 46
Accessory Technologies 47
Hybrid Technologies 48
Tyre Technology 49
Tyre Inflation 51
Fuel-efficient Lubricants 53
Fuel Economy Gains from Oils 39
Headlights and Daytime Running Lights 40
Fuel-saving Driver Support Devices 57

6. IMPROVING THE FUEL ECONOMY OF DIESEL VEHICLES 63

The Benefits of Diesel 63
New Engine Performance 64
Diesel Vehicle Shortfall 65
Low Ambient Temperatures 65
Aggressive Driving 66
Traffic Conditions 66
Effects of Other Technologies 68

7. TECHNOLOGY COSTS AND POLICIES TO PROMOTE TECHNOLOGIES THAT IMPROVE FUEL ECONOMY 69

Technology by Location Class 70
Technology Payback Period and Cost per Tonne CO_2 Reduction 71
Policies to Promote Technology Introduction 78

REFERENCES 81

EXECUTIVE SUMMARY

There is a gap between light-duty vehicle fuel economy as measured on official certification tests in OECD countries and actual on-road fuel economy[1]. The existence of this gap, or shortfall, is widely known and some countries already adjust test fuel economy values by a correction factor to account for it. In recent years, there has been speculation that the gap is growing as a percentage of the certified, tested value. This has raised concerns that national fuel consumption reduction goals based on test values will not be met in reality and that consumers will lose faith in reported fuel economy figures. This report analyses available data on the gap and examines technologies available to reduce it along with policies to promote their adoption. This information can be used to select technologies and measures for reducing oil use and CO_2 emissions that deliver fuel economy improvements on the road in spite of any deficiencies in the test cycles used to measure it.

An extensive review of the literature reveals that there have been few recent assessments of shortfall in OECD countries. New empirical studies are needed and would be very valuable. These could be conducted, for example, by having a sample of drivers keep logs of vehicle travel and actual fuel consumption, in different areas and for different types of vehicles, and then comparing this data to test-rated fuel economy figures.

An engineering analysis of available technologies has identified several that have little or no impact on fuel economy test results but are potentially useful for improving actual on-road fuel economy. Some (though not all) of these are estimated to be cost-effective for reducing fuel consumption from the consumer's viewpoint, based on a payback period[2] of three years. More of the technologies, in more situations, are estimated to provide net benefits to society – i.e. their costs are more than offset by the private plus the social benefits derived (associated with fuel savings and reduced oil dependency) – and they provide relatively low cost CO_2 emissions reductions.

The most cost-effective technologies are related to reducing the fuel economy shortfall for gasoline vehicles in cold ambient temperature and dense traffic conditions. These technologies are electric water pumps, energy efficient alternators, heat batteries (for pre-warming engine oil on start up) and 5W-20 oil. Under cold ambient, dense traffic conditions, the combination of all these technologies could increase fuel economy by around 10% on average and up to 20% during the winter. These benefits are available to urban drivers in areas such as Northern Europe, Canada, the Northern U.S. and Northern Japan. This is a promising area for policy intervention.

These and other technologies are sometimes cost effective in other situations (such as warmer climates or highway driving conditions) depending on fuel prices and average annual distances driven. A number of technologies were found not to be cost-effective in any of the conditions considered.

In addition to technologies, one non-technology measure was also considered: driver training programmes. With careful programme design, driver training can provide significant fuel savings and appears cost-effective in all driving conditions. A key assumption is that drivers continue to follow the recommended driving styles after the period of training. Several technologies are available to encourage fuel-efficient driving (such as shift indicator lights and fuel-use indicators) and are already provided in many cars. When incorporated in new vehicle designs they can be added to cars at very low cost (less than 10 or Dollars / 10 Euros).

Literature Review

Very detailed studies of shortfall completed in the early 1980s continue to be the only comprehensive sources of data to date. A small number of limited studies on shortfall have been conducted since then but the only significant source of data on in-use fuel economy is from a survey in Canada. The findings do not suggest that shortfall has increased dramatically in the last 20 years, or that the causes of shortfall identified earlier have changed markedly. In that period, only the EU has changed its test procedure, by adding the ‘extra urban’ cycle, and this has probably not significantly affected the level of shortfall.

The findings of the most comprehensive studies on shortfall in the early 1980s showed that:

- Shortfall increases as a percentage with increasing absolute fuel economy (measured in MPG or km/l).
- Light trucks have higher shortfall levels than cars.
- Shortfall is also a function of vehicle drive-train technology and possibly manufacturer specific calibrations.

The 1995 Canadian survey of on-road fuel economy showed results largely consistent with the findings from the 1980s in both magnitude and trend. Researchers have speculated that shortfall may be increasing either due to worsening traffic condition and higher highways speeds, or due to changes in vehicle technology (direct injection engines, hybrid technologies). This may be true but remains unproven with real world data. Road test data by magazines and TV programs do show manufacturer and technology specific shortfall differences, but the small sample of vehicles and unrepresentative test conditions do not permit any significant conclusions to be drawn.

Recent programs promoting driving-style improvement through training and technology aids show that improvements in fuel consumption of around 10% are possible from training, although drivers generally require feedback instrumentation to maintain performance. (The driver training effect assumes the maintenance of more constant speeds but does not assume a speed reduction.) The significant contribution of driving styles to shortfall was recognized even in the studies conducted 20 years ago, and similar margins of improvement were thought possible then.

Technologies to Reduce Shortfall

A wide variety of fuel-economy technologies have been adopted by vehicle manufacturers since the 1980s but a majority of them have little or no effect on shortfall. Some technologies, notably electronic engine management systems, can increase shortfall by tailoring engine operation to the test cycle. Other technologies, such as diesel engines and, possibly, gasoline direct injection engines, could reduce shortfall under many operating conditions. Small diesel-engine-powered vehicles typically have much lower shortfall than gasoline-powered vehicles because a diesel engine requires less cold start and acceleration fuel enrichment and uses much less fuel when the vehicle rests “at idle”. Therefore, while the technologies listed below are also applicable to diesel powered vehicles, technologies related to cold-starts and idling offer much larger benefits for gasoline engines.

A number of technologies aimed at improving gasoline vehicle fuel economy in off-test-cycle conditions (i.e. travel situations that are different from those characterized during test-cycle measurement) have been developed but have generally not penetrated the market. These technologies include:

- Electrically driven oil and water pumps.
- Efficient alternators.
- Efficient air conditioners and heat pumps.
- Fast engine warm-up technologies.
- Aids to improve driving habits.
- Idle-off systems.
- 42V electrical systems.
- Adaptive cruise control.

The reason that such technologies are not included in most vehicles is wholly or partly due to their limited benefit on the fuel economy test cycle.

In addition to these technologies, tyres and lubrication engine oil can impact on-road fuel economy and reduce shortfall. These are replaced periodically over a vehicle’s life and the replacement market is not well optimized for fuel economy. Tyre “rolling resistance” varies considerably by tyre model and the best tyres can reduce fuel consumption by several percent compared to average types. Yet no tyre rolling resistance information is available to consumers in most OECD countries. Increased monitoring of tyre pressure could also yield some fuel savings; it should be possible to adapt tyre safety-related pressure monitoring systems to provide information on moderate under-inflation as well, with low-inflation indication provided to drivers via a dashboard signal. Data on the average type of oil actually used in the replacement market is limited, but small benefits in fuel economy might be realized if the market for fuel efficient replacement oil were to be optimized.

Engine-related maintenance actions (in contrast to other maintenance actions such as tyre pressure monitoring and replacement tyre and oil choice), do not now have much impact on shortfall. This is because engines are designed to need maintenance less often than they used to, because electronic engine controls have made tampering and maladjustment difficult, and because emission inspections in most OECD countries provide strong incentive for yearly or biennial vehicle maintenance.

One emerging problem is the replacement of standard electronic engine management system components with customised control chips, designed to maximise performance in terms of power output in on-road conditions regardless of the effect on exhaust emissions and fuel consumption. This was not examined in this report but anecdotal evidence suggests it may be a growing contributor to shortfall.

Aggressive driving continues to be a major factor contributing to shortfall. A number of technological aids to assist the driver to drive in a more fuel-efficient manner are available. The literature review shows that real world gains of 5 to 10% in fuel economy are possible, on average, from the impacts of these technologies (combined with driver training) on improved driving habits.

Technology Fuel Economy Impacts and Cost-effectiveness

The literature review and engineering analysis presented in this report document a number of technologies available to reduce shortfall. The term “available” is used to indicate that no technical barrier exists for commercialization, but the technology has seen only limited or no introduction yet in the market. This is partly because auto-manufacturers will be able to claim little or no fuel economy benefit on the official certification test and partly because ambient and geographic conditions vary greatly among OECD countries from region to region and even within countries. Since the benefits of technologies in terms of reducing shortfall are often significant only under specific ambient/traffic conditions, manufacturers are unwilling to standardize these technologies across an entire model line. It may not be possible to find a “one size fits all” solution to the issue of technology under-utilization. Technologies most useful to Sweden or Canada sometimes have limited value to consumers in southern France or the southern States of the U.S. Similarly the ranking of technologies by cost-effectiveness varies with local conditions.

There are two types of important distinctions in terms of ambient conditions affecting shortfall: temperature (cold or hot) and traffic (dense or light, typically corresponding to large city or small city/rural conditions). The distinctions are somewhat subjective, but for this analysis the following characteristics were assumed for each situation:

- Locations with cold ambient temperatures - where daily low ambient temperatures are below 10°C for over six months.

- Location with hot ambient temperatures - where daily high temperatures exceed 25°C for over six months.

- Dense traffic, with city-wide average speeds below 25 km/hr (16 mph).

- Light traffic, with city-wide or rural average speeds in excess of 40 km/hr (25 mph), corresponding to freely flowing traffic.

When the two ambient conditions are combined with the two traffic conditions, they create four driving situations. Although some technologies have benefits that fall across all four of these quadrants, most technologies perform well only for one or two.

Thirteen technology options to reduce shortfall for gasoline vehicles were examined. The technology cost, or more accurately the retail price equivalent, (an estimate of how much the retail price for vehicles would increase under competitive conditions if the technology were added to the vehicles) was estimated for each option.

Technology fuel economy benefits were estimated using limited test data available in the literature and drawing on well-understood engineering relationships. Assumptions behind each estimate are described in the following chapters. Results are shown in Figure E-1, which shows that the potential benefits per technology are generally small, in the range of 1 to 5%, with only three exceptions: for idle stop/start in dense traffic; driver training in light traffic; and adaptive cruise control in light traffic conditions[3]. As would be expected, certain technologies provided a benefit only under certain conditions; for example efficient air conditioners in hot ambient conditions and idle stop/start under dense (i.e. stop/start traffic) conditions.

Given the different effects of technologies in different situations, the overall benefit to each driver depends on the share of driving done in each situation. To estimate average effects across all drivers in a country, the aggregate driving shares in each situation should be estimated. It should also be noted that technology benefits are not necessarily additive; for example, adaptive cruise control performs a function similar to driver training and applying both will result in less benefit than the sum of their individual effects. Combined effects have not been estimated in this study, except a general estimate that application of all, or even most, of these technologies should combine to reduce fuel use by 10% or more.

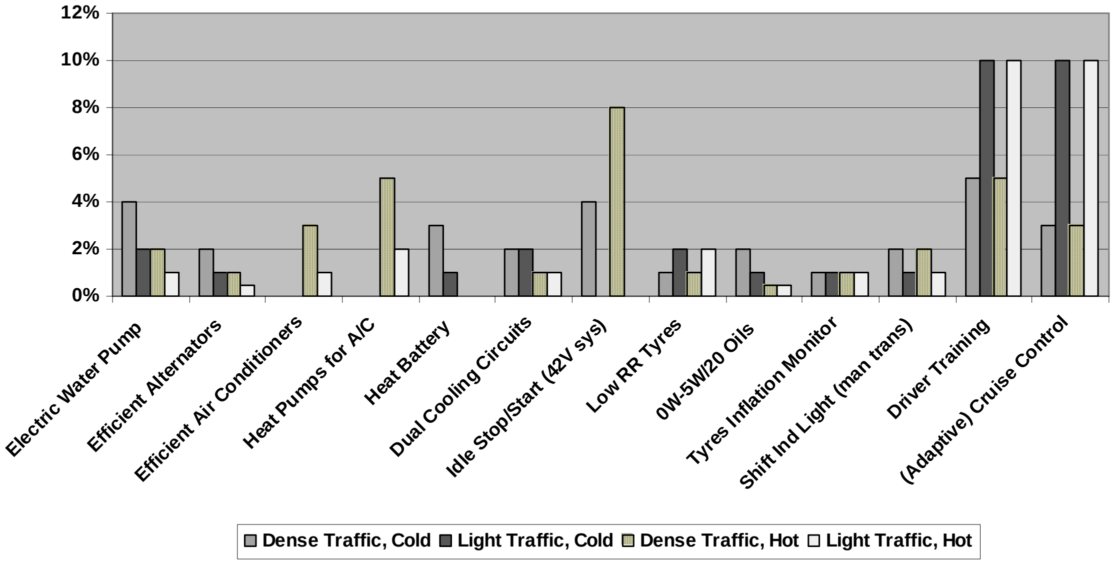
For diesel vehicles, the fuel savings achievable were found to be generally similar or slightly lower than those for gasoline vehicles. The biggest differences concern electric water pumps and idle stop/start. These are only about half as effective for diesels as for gasoline vehicles. On the other hand, adaptive cruise control impacts on diesels are 50% bigger – with an estimated 15% reduction in fuel use per kilometre, compared to 10% for gasoline vehicles.

One measure of technology cost-effectiveness is the time required to pay for the technology from the fuel savings. This metric relates to consumers' willingness to pay for this technology (and therefore manufacturer's willingness to put technologies into the vehicles they sell). The pay-back period is a function of local fuel prices, annual driving distances and baseline vehicle fuel economy.

Three cases are considered as examples of the range of these variables encountered among OECD countries. These cases are:

- **US gasoline vehicle:** fuel cost of $1.50 per gallon (Euro 0.32 per litre), with a baseline fuel economy of 27 mpg (8.7 l/100 km), driven 12 000 miles (19 200 km) annually.
- **EU gasoline vehicle:** fuel cost of Euro 0.90 per litre ($4.25 per gallon), with a baseline fuel economy of 7.5 l/100 km (31.4 mpg), driven 15 000 km (9 300 miles) annually.
- **EU diesel vehicle:** fuel cost of Euro 0.75 per litre ($3.55 per gallon) with a baseline fuel economy of 5.6 l/100 km (42.0 MPG), driven 18 000 km (11,200 miles) annually.

Figure E-1. **Estimated Fuel Savings (Percent) under Different Ambient Conditions for Gasoline Vehicles**

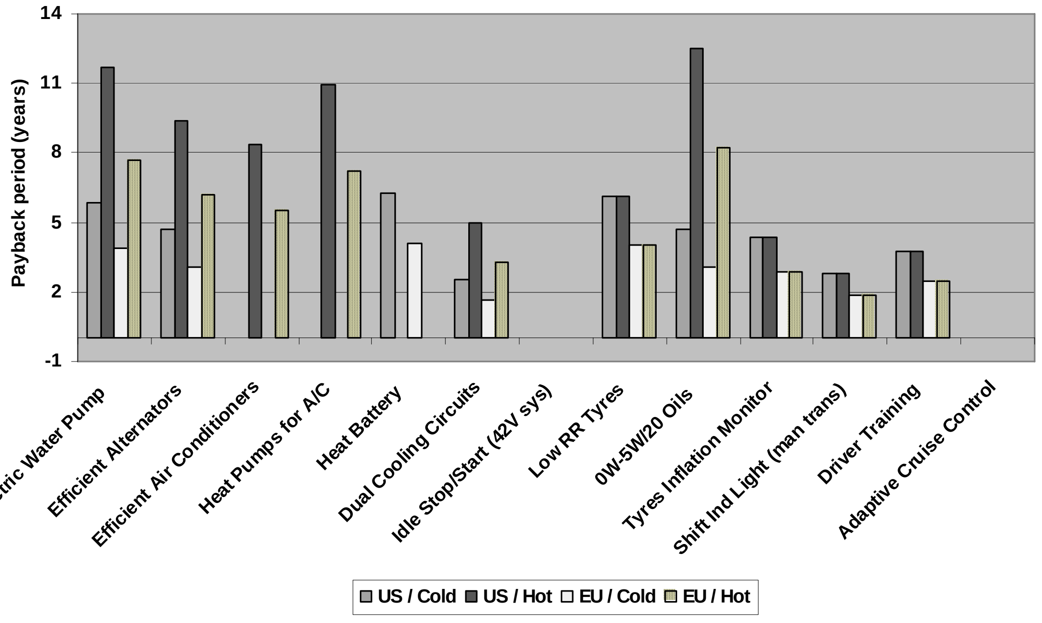


Source: Analysis presented in Chapters 5-7.

A second measure, of “social” cost and benefit, was also calculated for each technology in each situation, using CO_2 emissions reduction cost-per-tonne as the metric. This was calculated using an estimate for untaxed fuel cost ($0.40 per litre) and discounting fuel use over average vehicle life at a social discount rate of 3% per year. The results of the analysis on a payback-period and CO_2-cost basis are summarised below, and presented in more detail in the final chapter of the report.

Under the assumptions of a gasoline vehicle in Europe, with a regime of European fuel prices, fuel economy and average driving levels, several gasoline engine technologies are cost-effective from the consumers' viewpoint, especially at cold temperatures. This is illustrated in Figure E-2 in the form of payback times shown for cold and hot ambient conditions (and assuming a 50/50 share of driving in light and heavy traffic conditions). Under cold ambient conditions in the EU, most technologies, except for idle stop and adaptive cruise control, are paid for by fuel savings in three years or less, and should therefore be attractive to many consumers. Under hot ambient conditions, the situation is less favourable to most technologies. This is to be expected since the test procedure represents hot ambient conditions well, and cost effective technologies are likely to be already introduced as a result of market pressure. Under assumptions of a gasoline vehicle in the US, the situation is less favourable, mainly since taxed fuel prices are much lower than in the EU. The low prices are partly offset by higher fuel use, but only partly.

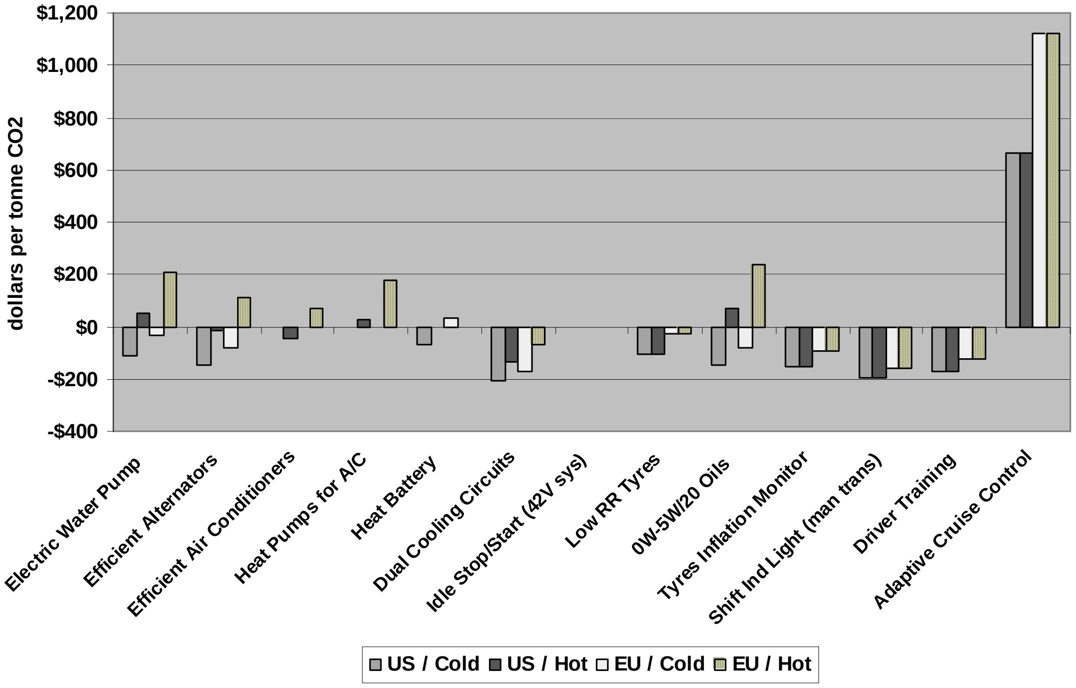
Figure E-2. **Technology Payback Period (Years), Gasoline Vehicles**



Source: Analysis presented in Chapters 5-7.

Results on the basis of net cost-per-tonne of CO_2 reduction are presented in Figure E-3. Instead of average taxed fuel prices, which are the relevant figures for evaluating consumer pay-back times, the estimates in Figure E-3 are based on resource costs: i.e. an untaxed retail fuel cost of $0.40 (reflecting about $36/bbl oil price, plus refining, transport and retailing costs). Fuel use during the first 10 years of vehicle life is included, at 3% per year social discount rate. No external or social costs are added to this price, in part to keep the cost-effectiveness estimates conservative (adding external costs related to oil use and dependency would raise the value of fuel saving and lower CO_2 reduction costs). Never-the-less, the results tend much more towards cost-effectiveness than they do from the consumer pay-back approach. Most technologies are cost effective (have a low or negative cost per tonne CO_2 reduction) in at least one of the geographic/ambient circumstances considered. Nearly all of the technologies reduce CO_2 emissions for under $100 per tonne in at least some situations, which although high in relation to the cost of some CO_2 reduction strategies in other sectors, is fairly competitive with other options for reducing CO_2 emissions in the transport sector. Most of the technologies reduce CO_2 for less than zero cost in at least some situations (i.e. the value of fuel savings to society is greater than the cost of technology). These are clearly "no-regrets" technologies from a societal point of view. Results are somewhat better for US conditions than for Europe, since in this case the same fuel cost is assumed for both regions while US fuel use per vehicle per year, and thus the potential fuel savings, remains significantly higher than in Europe.

Figure E-3. **CO_2 Reduction Costs ($/tonne), Gasoline Vehicles**



Source: Analysis presented in Chapters 5-7.

The literature review, mainly from U.S. studies, suggests that driver training often is not terribly cost effective. However, the Netherlands has successfully exploited driving simulators for training at much lower cost than estimated in the North American examples – extending the conditions in which appropriate driver training shows good returns. The Netherlands' estimates are used here, showing that driver training has short payback times and near-zero cost per tonne for CO_2 reduction.

The diesel case is less conducive to technology introduction partly because of lower fuel cost savings and partly because diesel engines use less fuel during cold start. However, shift indicator lights are cost effective for diesels in all ambient and driving conditions, and driver training and tyre pressure indicators appear to be at the margin of cost-effectiveness for the consumer. Under U.S. vehicle and fuel price assumptions, only a few cold-start related technologies are cost effective to consumers in cold ambient conditions. Adaptive cruise control is far from cost-effective under all scenarios, and will only be marketed for reasons other than fuel economy. From a CO_2 reduction cost point of view, most technologies are found to be almost as cost effective as they are for gasoline vehicles.

The cost-effectiveness analysis provides a good illustration of why most of the 13 technologies identified have not made much headway in the market. Even at fuel prices prevalent in the EU, most technologies are not very cost–effective for consumers (payback times exceed three years), or are cost-effective only under the cold ambient/dense traffic conditions case. The notable exceptions are the shift indicator light (SIL) and the dual cooling circuit system together with driver training (following the European rather than North American approach). The SIL, applicable to manual transmissions, has already penetrated the U.S. market but has not penetrated the EU, possibly due to the fact that manufacturers do not get any fuel economy credit for its adoption on the test procedure. The dual cooling circuit requires an engine cooling system redesign, and is likely to be introduced slowly as gasoline engines are updated or redesigned. The costs of this technology are primarily associated with capital investment in redesign, and best accomplished at the beginning of a product cycle for each engine model.

In contrast to modest cost-effectiveness of gasoline technologies for consumers, most of the technologies appear to be quite cost effective from a CO_2 reduction point of view, suggesting that government intervention is merited to bring these technologies into the market and achieve the potential social benefits they offer.

A number of gasoline vehicle technologies are cost-effective from both consumer and societal viewpoints, and are primarily associated with shortfall reduction in cold ambient temperature and dense traffic conditions. These technologies include the electric water pump, energy efficient alternator, heat battery (for pre-warming engine oil on start up), dual cooling circuits and 5W-20 oil. Under cold ambient dense traffic conditions, the combination of all these technologies could increase fuel economy by over 10%, on average, or up to 20% during winter months. These benefits are available to most urban locations in Northern Europe, Canada, the Northern U.S. and Northern Japan. This is a promising area for policy intervention.

For diesel vehicles, methods to discourage high speed driving and discourage shifting gears at high RPM appear to be the most cost-effective areas for intervention. However, perhaps due to the inherently lower shortfall observed for diesel vehicles in the early literature, there has not been much focus on examining the impact of on-road conditions on diesel vehicle shortfall. More research on diesel shortfall is warranted given the current rapid dieselisation of European passenger car fleets, and indications from the small number of more recent tests in Europe that shortfall in modern diesels may be much larger than for older diesel technology.

Policies to Promote Technology Introduction

A clear message from the available information on shortfall is that current test procedures in both the US and EU do not accurately measure average on-road fuel economy of light-duty vehicles. On-going efforts to better understand real world driving cycles and adopting these in revised test procedures would help to minimize this inaccuracy. Governments have shown a reluctance to revise test procedures, perhaps due to the complex and controversial nature of establishing them. The EU did revise their fuel-economy test procedures in the 1990s, and the US does provide an adjusted fuel economy figure on labels shown on car windows at dealerships, that reflects an assumption of lower on-road than test MPG performance. But these steps appear insufficient to encourage manufacturers to widely adopt the technologies covered in this report.

Short of revising fuel economy test procedures, a number of other policies may prove useful to encourage wide-spread adoption of these technologies, particularly the more cost-effective ones.

Providing information to consumers on the benefits of technologies in different situations (particularly cold temperatures and heavy traffic conditions) would be a positive step but may provide only limited motivation for their adoption. As noted, the net effect of any one technology is only a few percent reduction in fuel consumption, and the cost-effectiveness is often marginal (three to four years payback) from the consumer's viewpoint. However, many of the technologies are quite cost-effective from a societal point of view; further, some technologies also have pollutant emission benefits at cold temperatures and the full cost of these systems need not be allocated to fuel savings alone. Many OECD countries have cold temperature emission limits that could be made more stringent to force adoption of these technologies. Modest fiscal incentives to manufacturers in the range of Euro 100 ($120) per vehicle to reduce fuel consumption under cold ambient/slow speed conditions could promote their use, at least in some countries and regions.

It may also be possible to utilize voluntary agreements with manufacturers to introduce cost-effective technologies in specific locations. For example, home air conditioners are now required to meet a certain minimum efficiency level in the U.S. A similar (but voluntary) agreement could be reached on vehicle air conditioners. Similar agreements could be made regarding the uptake of other efficient technologies.

As discussed, driver training is cost-effective, assuming drivers do not lapse into old habits once the training is over. The technology to support fuel-efficient driving is already available in many cars, or can be added at very low cost (less than $10). Government subsidized training programs appear to be a viable means to provide the required training. Such programs should be instituted along with publicity about the programs, and subsequent popularization with fuel-efficient driving contests, etc.

Finally, programs can be implemented that encourage consumers to purchase more efficient after-market products such as replacement tyres and oils. Better information, rating systems and labelling are an important step. But stronger measures such as differentiated tax/subsidy systems based on product performance, might provide bigger responses and help achieve important social benefits.

Overall, it appears that there is an opportunity to improve average vehicle on-road fuel economy by 10-15% at low cost, but it will require government actions to achieve this. Governments are encouraged to explore the various policy options available to them, and select a set of technologies to target that provide strong social benefits in the particular context (predominantly cold or warm climate, urban v. rural, fuel prices, average travel distances and baseline vehicle fuel economy levels). Of course, there are "scale economies" to developing consistent incentives across markets, so adoption of single policy systems at the US or EU level may help send the strongest signals to the market, and avoid confusion.

Finally, this report is the first in many years to seriously explore this topic, and a key finding is that much more data and analysis is needed. Vehicle testing programs to estimate actual on-road fuel economy, and how it various by various situations and vehicle types, would be extremely useful. Further work to test the benefits of various technologies in reducing fuel economy shortfall, especially for diesel vehicles and new vehicle types such as hybrids, is also much needed. A study that includes systematic in-use testing of hybrid-electric vehicles would be particularly useful, especially as more models come into the market over the next few years.

NOTES

1. Various terms are used to refer to vehicle fuel consumption rates, such as "fuel economy", "fuel efficiency" and even "fuel consumption". Throughout this publication "fuel economy" is used. It is generally measured in litres per 100km. In some places in the text mile-per-gallon (MPG) equivalents are also provided.

2. Payback period is defined as first cost of the technology divided by the value of annual fuel savings.

3. The cost of adaptive cruise control was found to prevent it from being a cost effective option for saving fuel, and conventional cruise control available already in the market achieves similar savings at much lower cost. However, adaptive cruise control may also provide important safety benefits.

1. INTRODUCTION

All vehicle technologies have some effect on both test cycle and on-road fuel economy. For some the percentage reduction in fuel consumption achieved on the road is quite similar to that recorded on standard test cycle results. For others there can be significant differences. This difference is frequently termed "shortfall". While the test cycle has defined conditions, on-road conditions are highly variable. Technology evaluations of shortfall must therefore focus on the specific on-road conditions that are most responsible for shortfall.

This report describes how technologies and other measures affect and can contribute directly to reducing fuel consumption and investigates how they influence the *measurement* of fuel consumption through their relations with the parameters of vehicle fuel economy test cycles. The measurement of vehicle fuel economy is important and it appears that there has been a sizable gap between the official test cycle emissions and actual on-road vehicle emissions for some years. This gap, or shortfall, undermines the official measurement of CO_2 emissions and the achievement of national fuel economy targets as well as consumer faith in the reported fuel economy performance of vehicles. Knowledge of the causes of shortfall can be used to improve the test cycles themselves or to correct the results of existing cycles, to provide a more accurate value of emissions and so ensure that consumer expectations and Government targets are met.

Most importantly this knowledge can be used to select approaches to reducing CO_2 emissions that deliver fuel economy improvements on the road in spite of any deficiencies in the test cycle. From this perspective the report investigates the range of new technologies available to vehicle manufacturers and the policies available to governments to make significant improvements to vehicle fuel economy, through both technical and non technical means. The analysis for the report was undertaken for the International Energy Agency (IEA) and the European Conference of Ministers for Transport (ECMT) by Energy and Environmental Analysis, Inc. with input also from the Dutch energy agency NOVEM.

It should be noted that the report examines technologies for light-duty vehicles. Heavy-duty vehicles are not included nor are technologies that improve system performance by making traffic flow more smoothly. These issues, while important, are beyond the scope of this report. It should also be noted that driver behaviour is only addressed in so far as it conditions the impact of the technologies reviewed on fuel economy. Driver training, and instrumentation to provide feedback to drivers on the effects of their driving style on fuel consumption, is a key avenue for reducing CO_2 emissions and resolving test cycle shortfall issues in its own right.

In carrying out the analysis presented here, the first task was to review previous studies on the subject. Much of the existing body of work on shortfall was undertaken in the late-1970s and early-1980s during the fuel crises. Since that time, there have been very few studies on shortfall, and none are as comprehensive as those conducted 20 years ago. A review of these studies is presented in Chapter 2. More recent studies do not contradict earlier results but the number of vehicles sampled in these studies is generally too small to draw definitive conclusions. However, they do provide further insight into the causes and nature of shortfall.

The second task was to examine new technology being introduced into vehicle fleets and use engineering analysis to estimate trends in shortfall as a result of technological change. The third task also deals with technology, identifying available technologies that could be introduced to reduce shortfall. Both tasks are covered in Chapter 5 for gasoline engine powered vehicles and in Chapter 6 for diesel engine powered vehicles. The analysis builds on the findings of the literature review.

The final task was to develop "cost curves" of technologies and actions to reduce shortfall, and to identify policies to encourage the uptake of cost-effective technology. The results are presented in Chapter 7.

The study found that due to the substantial variability of ambient and traffic conditions, it was not possible to develop a single "supply curve" for technology applications. Rather, sets of technologies best suited to shortfall reduction in specific climatic and traffic conditions were identified, and policies to promote their uptake are suggested.

2. LITERATURE REVIEW OF “SHORTFALL”

As noted in the introduction, the major systematic studies of fuel economy shortfall between official certification test fuel economy and on-road fuel economy were completed in the late 1970s and early-1980s. The studies identified the causes of shortfall, and also estimated the magnitude of shortfall from surveys of vehicle owners. It is widely known that vehicle owners can have fuel economy significantly different from the official test value, but governments generally believe that test values should not be so biased that the vast majority of drivers experience lower fuel economy than the official value used for consumer information. Hence the U.S. publishes estimates of fuel economy for consumers that are discounted from the measured test value; the city cycle value is discounted by 10% and the highway cycle value by 22%. These discounts have not been changed for the last two decades; similar adjustments have been used in some other OECD countries, though not in Europe. There has been no recent large scale study involving survey data to see if the adjustment factors are still appropriate for modern vehicles.

The detailed studies conducted in the early 1980s do, however, provide useful insights for examining how new technologies and changes to vehicle designs affect shortfall. The discussion below provides a framework for examining the effects of new technology on shortfall.

The on-road fuel economy of a specific vehicle is sensitive not only to the vehicle technology but also to the local geography, ambient conditions, driving technique and vehicle state of maintenance/age. Hence, a given vehicle type can have significant differences in fuel economy depending on its owner and location. These facts have been widely recognized, and most government fuel economy programs have a disclaimer on the accuracy of the test fuel economy.

The late-1970s and early-1980s were periods when considerable work was done by regulatory agencies in Europe, North America and Australia to examine the issue of shortfall. Several reports provided a compendium of available information on this topic, including one published by the OECD[1] in December 1981 and another published by the U.S. EPA[2] in Fall 1980. The two reports identified very similar sets of causal factors, although the USEPA report provided more quantitative characterization of the effect of each causal factor.

Given that test fuel economy is measured under a specific set of ambient conditions and with specific driving cycles, the main reasons for shortfall can be grouped as follows:

- Ambient conditions.
- Mix of driving cycles and trips.
- Road conditions and topography.

- Vehicle state-of-maintenance.
- Driver behaviour.
- Vehicle accessories and cargo.

These factors and their effects on fuel economy as characterized in the OECD and EPA reports are summarized below.

Mix of Driving Environments

The mix of driving environments refers to the mix of city, suburban and highway driving (as distinct from the cycle aggressiveness, which seeks to reflect driver behaviour). Obviously, this mix is highly influenced by location and trip route, but many observers have commented on the fact that the "typical" mix used, say, by the USEPA or by the EU to report average fuel consumption is probably incorrect on average. The EU used to utilize a one-third each mix of urban, 90 km/hr highway and 120 km/hr highway fuel consumption values to derive a composite value, but a 1989 TRRL (UK) study[3] showed a mix of 60% urban, 26% at 90 km/hr and 14% at 120 km/hr was significantly better in matching "average" in-use consumption. The EU subsequently modified its test cycle, but the change is not thought to have significantly reduced shortfall.

Increased congestion levels in the suburbs and highways may lead to increasing fuel consumption, since city cycle fuel consumption in typically 30 to 40% higher than consumption at highway speeds. However, it is less of an issue for consumers since city and highway fuel economy are separately provided in most OECD countries.

Trip length is an important variable, especially from cold start conditions, for determining fuel economy. Short trips generally result in higher fuel consumption due to the need to warm up the engine to operating temperature. As noted, short trips at cold ambient temperature result in the greatest fuel economy penalty. Even if average trip length is correctly represented in the test cycle, the non-linear nature of the trip length effect will always result in on-road average fuel consumption being worse than measured fuel consumption (i.e., the improvement in fuel economy for longer than average trips does not compensate for the shortfall in shorter-than-average trips).

Higher levels of congestion with more extended idling also occur in many OECD countries, as the suburbs become as congested as the city-centre. Extended idling or "creeping" forward at very low speeds causes a very large fuel consumption penalty, but there is little analysis or data to provide estimates how much idling/creeping type driving has increased over the years for the entire vehicle fleet.

Road Conditions/Topography

The fuel economy certification test is conducted on a smooth tyre contact surface, and no simulation of gradients is employed. In the real world, twisting roads, unpaved surfaces and mountainous regions are also responsible for fuel economy reduction. In most countries, the effects of twisting roads and unpaved surfaces are quite small, on average, because they are infrequently encountered. Travel under these conditions is generally a small percentage of total travel, and the effect of winding roads and unpaved surfaces typically increases overall consumption by 2 to 5%. These conditions often act to reduce driving speed, which has a favourable effect on highway fuel economy.

Mountainous condition can be more common in some regions/countries and the effect on fuel consumption depends on the gradients encountered. Moderate gradients (less than 4 to 5%) impose very small penalties on fuel economy since much of the energy lost in climbing is recovered in the downhill phase of driving. Steeper gradients, involving operation in a lower gear, can have large effects since the climbing energy is also dissipated in braking downhill. Locations where steep grades are encountered are quite limited in most OECD countries, and such areas are also less populated, so that the average contribution to shortfall is typically limited.

Vehicle Accessories and Cargo

Many vehicles are equipped with a number of power accessories such as a stereo systems, power windows/seats, defrosters and air conditioning. Typically, most certification tests do not test vehicles with any of the accessories turned on. The U.S. test procedures simulate air conditioner use by utilizing a 10% increase in the setting of the power absorption unit on the dynamometer, and the test is not sensitive to actual air-conditioner performance. Typically, the use of these power accessories degrades fuel economy, but their effect can be seasonal. Defrosters and air conditioners can use significant amounts of power, but other accessories are not important contributors to shortfalls.

Of the accessory loads, only the air conditioner load is significant as a contributor to shortfall, since other accessories such as the electric defroster are not typically turned on for long periods of time. The air conditioner, when turned on, can decrease fuel economy by 10 to 20% depending outside temperature and vehicle engine size. In some OECD countries such as the U.S. and Australia, air conditioners may be used for six to eight months of the year.

An issue peculiar to light trucks is that many pickup trucks carry cargo or tow boats/campers, but the certification test does not reflect this fact. In fact, many OECD countries continue to test trucks at a test weight equivalent to the curb weight + 300 lbs. (136 kg), while many trucks operate with a load significantly more than just the driver and fuel load simulated on the cycle.

Studies of actual on-road fuel economy in the U.S. (which has the greatest prevalence of light trucks of all OECD countries) also show that light trucks have greater percentage difference in fuel consumption between on-road and test value than cars (see Section 2.2.7). Part of this difference can be attributable to greater use under loaded conditions.

Vehicle Technology-Specific Effects

Since shortfall is a function of many variables including location, season and driver behaviour, any assessment of average shortfall, and variations of shortfall by vehicle technology require large samples of data from an unbiased pool of consumers across all seasons and locations. Such large scale surveys were conducted by the U.S. DOE and EPA in the late 1970s and early 1980s and a 1982 SAE Paper by McNutt, *et al*.[5] summarized the results of several years of data analysis. Shortfall was measured as the ratio of actual fuel consumption to test fuel consumption, and the “gallons-per-mile” ratio (GPMR) was found to be sensitive to both technology and absolute fuel economy. Figure 2-1 shows the results by drive train type (front/rear wheel), transmission (automatic/manual) and fuel delivery (carburettor/fuel injected) type. Of course, in that time period, very few fuel injected cars were available, so the results for these vehicles are not necessarily representative of today’s vehicles.

The McNutt, *et al*. review of shortfall arrived at the following conclusions:

- Shortfall varied by model year, and vehicle technology. For the 1981 model year, the GPMR for cars was in the range of 18 to 24%.

- Rear wheel drive (RWD) carburetted cars with automatic transmissions had the highest level of shortfall (and were also the most common type of vehicle in the database).

- Manual transmissions, front wheel drive and fuel injection were technologies that reduced shortfall relative to the RWD, carburetted, automatic transmission equipped vehicle.

- However, data from the early 1980s showed increasing shortfall for some of the alternative technologies mentioned above.

- Diesel engine equipped vehicles were found to have lower shortfall, but this was based on a small sample of vehicles (more recent tests in the EU have shown large shortfalls with powerful diesel engines).

- Light trucks displayed higher levels of shortfall than cars for the same technology combinations.

- Shortfall is not a stable phenomenon but depends on the industry’s ability to optimize technology performance over a specific test procedure.

The last conclusion suggested that the lower shortfall for front wheel drive and fuel injected cars may have been an artefact of their relatively recent introduction at the time of the study. However, engineering analysis suggested that there were also plausible reasons why the technologies would have lower shortfall:

- Front wheel drive technology results in higher tyre loads on the drive wheels on the dynamometer.

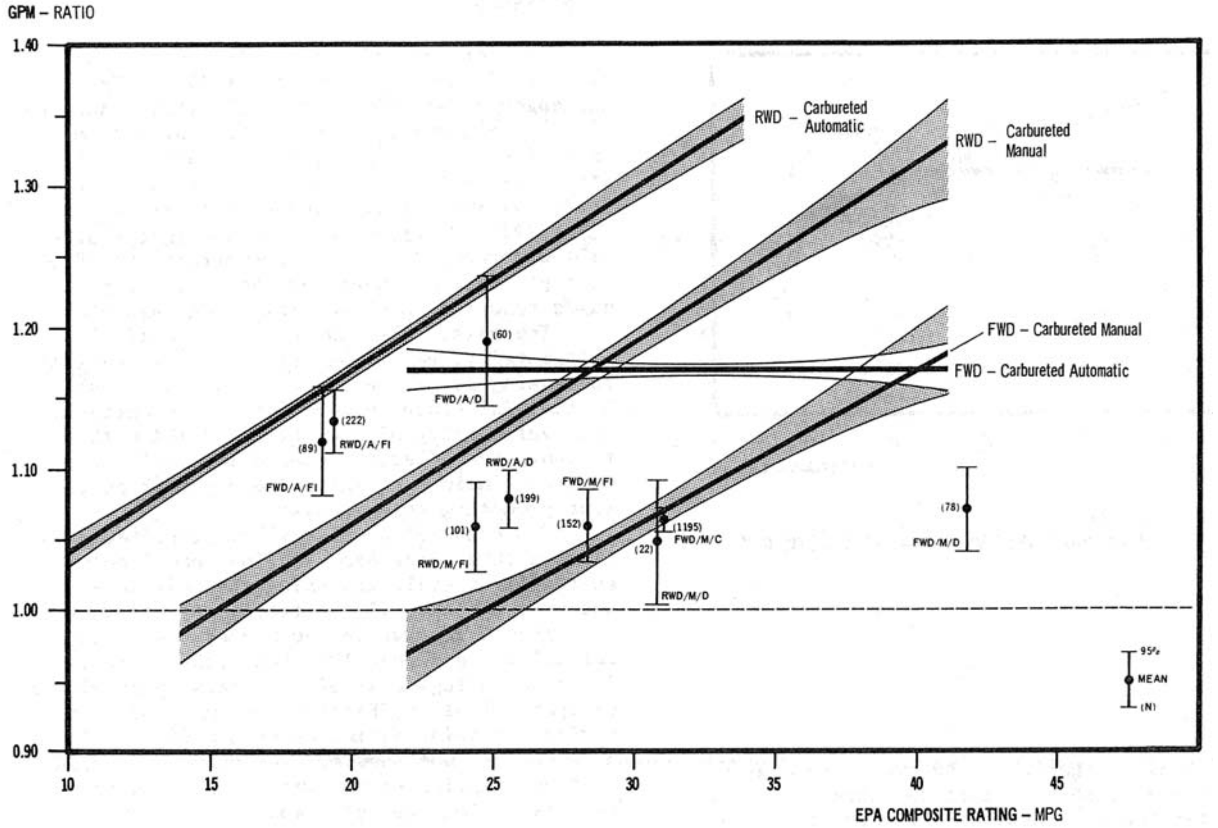
- Fuel injection reduces the need for acceleration and cold start enrichment relative to a carburettor.

- Manual transmissions could not have shift schedules optimized for the test-procedure (for which the shift points are specified), whereas automatic transmission shift points could be optimized for the test.

- Diesel engines have very low fuel consumption at idle, and require less cold start enrichment at start-up.

Hence engineering analysis would suggest that at least part of the reduction in shortfall observed should continue into the future for these technologies.

Figure 2.1. **Shortfall by Vehicle Technology**



Notes: RWD = rear wheel drive; FWD = front wheel drive; MPG = miles per gallon; GPM = gallons per mile.
Source: Reprinted with permission from Society of American Engineers (SAE) paper 820788 © 1982 SAE International.

Outside of Canada, no major data collection efforts involving large samples of data on in-use fuel economy have been undertaken since the mid-1980s. The TRRL (UK) published a study[3] in 1989 based on data obtained in 1984 on model year 1980 to 1983 cars, involving a total sample of about

3600 cars. The TRRL analysis found that on-road fuel consumption was best approximated by weighting the urban, 90 km/hr and 120 km/hr fuel consumption by 0.6, 0.26 and 0.14 respectively. This mix predicted on-road fuel consumption within ±10% of observed values for about 93% of all vehicles, although a simpler equation involving only city fuel economy was almost as good of a predicator of on-road fuel economy.

An important outcome of the study was the recognition that many car models exhibited on-road fuel economy substantially better or worse than would be predicted by regression analysis of measured to on-road fuel economy data. This suggests strong influences of both manufacturer specific calibration, and drive train technology.

Lee Schipper, *et al*.[6] have addressed the shortfall issue in several papers published in the early 1990s. These studies examined shortfall from the aggregate view of total fuel consumption. They pointed to a potential for increasing shortfall, but the studies did not estimate shortfall with levels of accuracy sufficient to estimate technology effects.

Mintz, Vyas and Couley of Argonne National Laboratory (ANL)[7] published a study in 1993 that utilized survey data on fuel consumption from calendar year 1985, with a sample of about 4 500 vehicles. They found shortfall of 18.6% for cars and 20.0% for trucks. Although the authors state that this is much higher than the EPA adjustment factor of 15% used for consumer fuel economy information, the results are consistent with the results cited by McNutt, *et al.* in that trucks have a higher shortfall and that shortfall increases with increasing absolute levels of fuel economy. The ANL study showed small cars and small light trucks to have the highest level of shortfall, and 1983-1985 model year vehicles to have higher shortfall than similar size 1978-1982 model year vehicles. Since fuel economy of the 1983-1985 vehicles was higher than those of the 1978-1982 vehicles, this result is consistent with shortfall increasing with absolute fuel economy.

Canada is perhaps the only OECD country that has continued to survey fuel consumption of on-road vehicles in the 1990s. The most recent analyses of survey data[8] was published by Natural Resources, Canada in 1999 using data from the National Private Vehicle Use Survey conducted in 1994-1996, with a final sample of about 7800 observations. Their data showed that actual fuel consumption was 23.1% higher than the "55/45" combined city/highway fuel consumption measured on the test for cars, and 27.9% higher for light trucks. Small cars showed a higher level of shortfall (25.3%) than large cars (22.5%). In addition, vehicles in urban areas had a shortfall of 26.4% compared to vehicles in rural areas with a shortfall of 17.4%. It should be noted that all of the findings are reasonably consistent with the detailed results from the McNutt, *et al.* paper published in 1983, because the test fuel economy values for these cars have increased significantly for the fleet since the early 1980s.

There have been a number of small scale "surveys" ranging from test data published in car enthusiast magazines to self-reported surveys conducted at websites. In general, data from enthusiast magazines are far less reliable as most car magazines test new vehicles in (typically) aggressive driving conditions for a few days. Web page surveys suffer from selection bias in that consumers voluntarily posting their fuel economy result may be unrepresentative of the population.

Some hybrid vehicles introduced in the U.S. have their owner websites, and one unpublished study by EPA[9] examined the owner reported website data for the Honda Insight and Toyota Prius. In these vehicles, the computer provides lifetime fuel economy on a display, so that the issue of erroneous owner computation of fuel economy is not relevant. The Honda Insight has an EPA test rating of 75.2 MPG for the five-speed manual transmission model, and the "real-world" average was 61.3 MPG from 127 data points reported on the website. The fuel consumption shortfall is 22.7%, a value similar to the shortfall for all cars reported in Canada. The Toyota Prius has a test rating of 57.6 MPG, and the real world average was 45.5 MPG, a 26.6% shortfall, based on a much smaller sample of 22 data points. There were two owners who provided actual fuel consumption data from tank refills (as opposed to computer generated data), and refill based fuel consumption was found to be almost 7% higher than computer calculated fuel consumption. While interesting, it is difficult to use these limited data for any statistically significant conclusions about hybrid car shortfall.

In Europe, we are not aware of any systematic study of shortfall, although there are many press reports and much anecdotal information on shortfall. There are reports in the British press on the supposedly poor on-road performance of hybrids. As an example, a recent (November 14, 2002) report on Wintons World (www.wintonsworld.com/cars)[10] claimed that car makers "routinely" exaggerated fuel economy, a claim based on data from road tests of at least 600 miles. The Toyota Prius with a combined EU fuel economy rating of 57.6 MPG actually delivered only 38.1 MPG on the road test, for a 33.9% shortfall. Several diesel vehicles such as the BMW 330d and Audi A2 1.4 TDI were also found to have a shortfall of about 33%. In related tests on BBC TVs "Top Gear" magazine, two Renault diesels were found to have shortfall levels of 30%.

At the same time, several gasoline and diesel powered cars were observed to have low levels of shortfall (less than 20%), suggesting that manufacturer-specific vehicle optimization, rather than only technology, could play a significant role in determining shortfall.

CHAPTER SUMMARY

Very detailed studies of shortfall completed in the early 1980s continued to be the only comprehensive sources of data to date. A small number of limited studies on shortfall have been conducted since, and their findings do not suggest that shortfall has increased dramatically in the last 20 years, or that the causes of shortfall identified earlier have changed. In that period, only the EU has changed its test procedure by adding the ‘extra urban’ cycle, but this may not have significantly affected the level of shortfall.

The most comprehensive findings on shortfall in the early 1980s showed that:

- Shortfall increased with increasing absolute fuel economy.
- Light trucks had higher shortfall levels than cars.
- Shortfall was also a function of vehicle drive train technology and possibly manufacturer-specific calibrations.

Surveys of vehicle fuel economy in 1995 in Canada showed results largely consistent with the findings from the 1980s in magnitude and trend. Others have speculated that shortfall may be increasing either due to worsening traffic condition and higher highways speeds, or due to changes in vehicle technology (direct injection engines with test-optimised electronic management systems and hybrid vehicles). This may be true but remains unproven with real world data. Road test data by magazines and TV programs do show manufacturer and technology specific shortfall differences, but the small sample of vehicles and unrepresentative test conditions do not permit any significant conclusions to be drawn.

Programs promoting driving style improvements, either through training or technology aids, show that improvements in fuel consumption of the order of 10% are possible, but motivating drivers appears difficult, even with higher European fuel prices. The significant contribution of driving styles to shortfall was recognized even in the studies conducted 20 years ago, and similar margins of improvement were thought possible then. Little has changed in the intervening period.

3. THE EFFECT OF AMBIENT CONDITIONS, VEHICLE MAINTENANCE AND DRIVER BEHAVIOUR ON FUEL ECONOMY

As noted in the literature review section, the major factors affecting shortfall are: (1) low ambient temperatures; (2) short trips, especially in combination with low temperatures; (3) aggressive driving and certain other driving behaviours; (4) mix of city/highway driving and actual driving speed under each conditions: and (5) use of the air conditioner. Other factors such as topography, road conditions, etc., are not major contributors to average shortfall, although they can be important in some specific areas. The technologies of particular interest to this study are those that have small benefits on the test but significantly greater benefits under in-use conditions. Those with the greatest impacts at low ambient temperatures and in other critical conditions are likely to be of most interest.

The Effect of Ambient Conditions on Fuel Economy

Major factors affecting fuel economy are temperature, wind and precipitation (rain, snow). The certification test is usually conducted at a temperature of 20°C to 25°C, whereas actual temperatures in most populated areas range from -30°C to +40°C. The test is also conducted under zero wind and precipitation conditions.

Of the ambient conditions, temperature has the most significant influence on fuel economy. The largest influence is when the engine is started from cold; during the first kilometre of travel from a “cold” start even at 20°C, the fuel consumption is up to three times higher than with a fully warmed-up engine. Both the OECD and EPA reports suggest a fuel consumption increase that is directly proportional to (30 – T)°C, where T is the ambient temperature, and inversely proportional to trip length. (Above 30°C there is no change to fuel economy.)

Even with the engine fully warmed up, low ambient temperatures reduce fuel economy due to greater heat losses from the engine and increased drive train and tyre friction. The OECD analysis suggests a change of the order of 0.2% per degree decrease in ambient temperature to 0°C and 0.5% from 0°C to -20°C. The cold start fuel consumption factor is much larger, but trip distance dependant.

Wind and precipitation can act to increase fuel consumption, but they have a relatively small average effect, partly because high wind conditions or heavy precipitation are relatively infrequent in most places, and driving is also typically reduced under these conditions.

The Influence of Vehicle Maintenance on Fuel Economy

Studies conducted in the late 1970s and early 1980s showed that several common defects in vehicles could increase fuel consumption by 10 to 20%. This included a rich mixture adjustment of the fuel metering system (carburettor, fuel injection) and the loss of spark to one or more cylinders (misfire). Repairs conducted on small samples of in-use vehicles (5 to 50 vehicles) in many countries showed average benefits in fuel economy in the range of 5 to 10%, with some vehicles experiencing much larger benefits. However, the benefits measured immediately after repair are not likely to persist indefinitely on the road.

The advent of emissions related inspection programs, now common in most OECD countries, as well as changes in engine technology, has made severe malperformance much less common now than in the 1970s. However, some small fraction of vehicles in the fleet will have malperformance that results in significant loss in fuel economy.

More modest effects of vehicle maintenance on fuel economy are associated with dirty air filters, use of higher viscosity engine/transmission oils, “sticky” brake linings and incorrect tyre inflation and wheel alignment. Dirty air filters can cause fuel economy to decline by up to 6% in older vehicles, but has smaller effects on modern vehicles with “closed-loop” air fuel ratio control. Surveys of vehicles in the U.S. found up to 10% of all vehicles with misaligned wheels, and up to 70% of all vehicles with tyre pressures lower than recommended. Tyre pressure reductions were stated to affect fuel consumption by 2.5 to 3% per psi reduction from recommended levels, according to the OECD report.

The literature review showed that in the 1980s, poor maintenance of some fraction of vehicles contributed significantly to shortfall. Repair or tune-up of in-use vehicles was found to provide average improvements of 5 to 10% in fuel economy, with some vehicles experiencing much larger improvements. Such large improvements are not likely in newer (post-1990) vehicles for several reasons. Most modern cars and light trucks sold in OECD countries feature electronic fuel injection and electronic spark control, and these technologies require no special maintenance or adjustment over the vehicle’s life. Indeed, some new vehicles advertise the ability of the engine to be operated with no “tune-up” over 100 000 miles (160 000 km). Most electronic systems also feature self-diagnostics, and serious problems are communicated to the driver and/or compensated for by the electronic control. Moreover, the electronic systems cannot be easily tampered with or maladjusted, problems common with carburettors and mechanically controlled ignition systems. In addition, most OECD countries have instituted some form of annual/biennial inspection program for emissions, so that vehicle owners cannot continue to operate indefinitely with malfunctions that increase fuel consumption and emissions, as in the past.

These factors, coupled with increasing reliability of engine controls, have resulted in very few vehicles failing the emission test even at quite stringent pass/fail standards. For example, inspection programs in the U.S. report failure rates of 5% or less for post-1990 vehicles, although the existence of the programs itself could be a major reason for better maintenance. Typically, any malperformance causing a significant increase in fuel consumption will cause a vehicle to fail the emissions test. However, some vehicles failing the test (especially those failing for high NO_x emissions) may not necessarily have reduced fuel economy.

An analysis of post-1985 cars failing the emission inspection and subjected to repair was conducted by EEA using data generated by U.S. EPA. On a sample of 116 vehicles, 71 vehicles experienced an average increase in fuel economy of 8.9%, while 45 exhibited a <u>decrease</u> of fuel economy after repair of 3.5%. While the post-repair average increase was still positive, the analysis shows that maintenance could decrease fuel economy for some fraction of cars. In addition, the relatively large average positive benefit for the 71 cars was due to a small subset of seven vehicles experiencing very large increases in fuel economy (>25%) due to replacement of failed oxygen sensors. These cars did not have self-correcting diagnostics, and such large increases in fuel economy with oxygen sensor replacement are unlikely in more modern vehicles. Hence, engine maintenance issues can no longer be considered as having a significant influence on shortfall.

The Importance of Driver Behaviour for Fuel Economy

Driving styles introduce large variations in fuel economy. Driver behaviour is complex and can be characterized by numerous independent parameters. Among the most influential behavioural factors effecting fuel economy are:

- Selection of gear change RPM (engine speed – revolutions per minute).
- Acceleration and deceleration patterns.
- High speed driving.
- Prolonged idling.

ECO-DRIVING Style Recommendations (from NOVEM)

- Shift up as soon as possible. For petrol/LPG cars at a maximum of 2 500 RPM, for diesel cars at a maximum of 2 000 RPM.
- Maintain a steady speed, using the highest gear possible.
- Look ahead as far as possible and anticipate movement of surrounding traffic.
- When slowing down or stopping, decelerate smoothly by releasing the accelerator well ahead of time and coasting, leaving the car in gear.

Source: *Interpretation of Driving Style Tips*, TNO Automotive, report for NOVEM, 2002.

Many consumers are to some extent aware of the fuel economy consequences of hard acceleration and high speeds but choose to drive in a non-fuel economy-maximizing manner due to the non-monetary benefits they perceive. Nevertheless, behavioural changes can increase fuel economy significantly[11]. Results from studies conducted in Europe and the U.S. have suggested fuel economy gains of 5 to 20% are possible from driver training. In the last decades, the engine technology and performance of both passenger cars and trucks has improved rapidly, while most drivers have not adapted their driving style. Their driving is thus not suited to modern engine technology characterised by high power, high torque at low RPM, electronic engine management, turbo chargers and variable valve technology. "ECO-DRIVING" as defined in European countries such as the Netherlands and Switzerland is an adapted driving style, which best fits modern engine technology. ECO-DRIVING means smart, smooth and safe driving at lower engine speeds (1 200 – 2 500 RPM), which saves 10% fuel on average.

European governments have focused on the issue of on-road driving practices, and several programs to support "ECO-DRIVING" are underway in countries such as Netherlands, Sweden, Germany and Hungary. At a conference held in May 2002 at Utrecht the Swedish National Road Administration (Vagverket)[12] reported on the results of a training program for light-duty vehicles. About 1000 drivers were trained in Sweden on how to drive economically, and fuel consumption on a fixed circuit was measured before and after training. The decrease in fuel consumption measured was about 12 to 13%. Long-term follow-up indicated that fuel consumption decreases in real traffic were in the 5 to 10% range. Most of the drivers were commercial drivers and their employers had a strong incentive to save money.

While these studies show the potential for driver training, it should be noted that the results may be influenced by a self selection bias, i.e., the people who were trained in ECO-DRIVING courses were more interested to learn this driving technique relative to the general population. This bias disappears if the driving technique is part of the regular driving curriculum, as it now is in some countries.

Much experience has been gained by NOVEM in the Netherlands both with individual courses for licensed drivers and with training provided as part of driving school curricula. More than 90% of the instructors and examiners in the Netherlands have taken voluntary ECO-DRIVING lessons and been instructed in teaching the principles of this driving style to student drivers as well. Several ten of thousands of new drivers have been made familiar with ECO-DRIVING in driving lessons since 2002. ECO-DRIVING will be judged in exams from about 2005.

The individual courses have proven to result in savings of at least 10% on average and over 30% for some drivers. The reference for comparison is the driving style often taught in the past, that typically encouraged driving at too high RPM levels in too low gears and exaggerated vehicle dynamics (frequent acceleration / deceleration / high speed). However, much of the fuel savings may come from proper shifting of a manual transmission. This is not an issue for automatic transmission equipped vehicles, which are the majority of vehicles in North America.

The use of driving simulators in training courses has been found to save time and resources and is almost as effective as on-road training, and additional tools such as computer games on CD-ROM and Internet have been developed for learning ECO-DRIVING at home.

The main group of licensed car drivers who are accustomed to the “old driving style” that is not suited to modern engine technology (high power, high torque at low RPM, electronic engine management, turbo-chargers and variable valve technology) are not addressed by the new driving curriculum. It is impossible to train the many millions of licensed car drivers in a few years with the available methods and training capacity and the existing limited awareness and willingness to spend money on driving courses. An alternative approach to stimulate a fuel-efficient driving style among licensed car as well as truck and bus drivers is to introduce feedback devices in vehicles, such as RPM gauges marked for fuel economy, fuel economy displays (using econometers or on-board computers), tyre pressure indicators, traffic information systems and shift indicators (see chapter 5).

4. DRIVING CYCLES AND SHORTFALL DATA

Investigation of driving cycle – emissions relationships has led to adjustments in regulations. The EPA and California Air Resources Board (CARB) have developed driving cycles that represent more aggressive driver behaviour and the European Unions regulations were adjusted to add an extra-urban element to the test cycle. Data from tests of vehicles on these cycles as well as the more standard driving cycles can be used to compute the effect of driving behaviour on fuel economy. These resulting fuel economy figures can also be used in conjunction with the parameters of the driving cycles to investigate the relationship. The EPA and CARB provided EEA with emissions data from cars tested on several driving cycles, and these were analyzed as follows.

Concern that the standard U.S. Federal Test Procedure's urban and highway cycles failed to capture the effect of more aggressive drivers on measured vehicle emissions led the CARB to develop a new cycle called the Unified Cycle. In 1996, as part of their program to evaluate the Unified Cycle (UC), CARB carried out an emissions study on 17 vehicles, comparing the emissions under this cycle to those produced by the same vehicles under the Federal Test Procedure (FTP) city cycle.[13] The UC is intended to represent aggressive city driving, with high rates of acceleration and deceleration, high maximum speeds but low average speeds, while the FTP (city) is a more conservative urban driving cycle, with starts and stops but lower acceleration and deceleration rates.

The key parameters of both cycles are presented in Table 4-1. The cycles are similar in their average and maximum speeds. However, the UC is significantly more aggressive in other respects. The UC's average acceleration exceeds the FTP (city)'s by 30%, while the maximum acceleration and deceleration are both over 100% greater.

Fuel economy data on the 17 vehicles tested over the two cycles showed that the fuel economy on the UC was significantly lower than that on the FTP. It is worth noting that all but one of the vehicles exhibited a decline in fuel economy on the UC cycle, with a maximum of a 14% decrease and an average of a 5% decrease in fuel economy on the UC relative to the FTP. Figure 4-2 shows the fuel economy decline relative to the FTP for the UC driving cycle for the 17 cars.

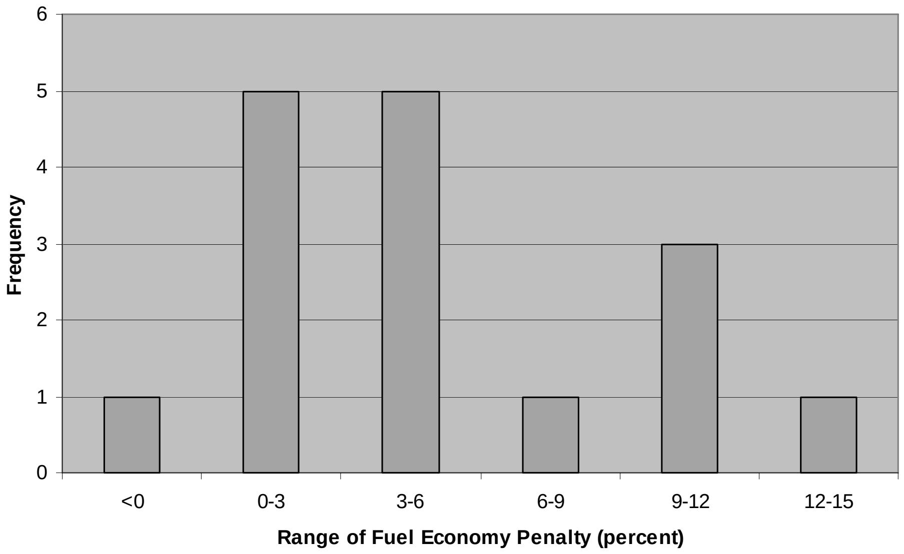
Figure 4.1 shows that there is considerable car-to-car variation in response, consistent with previous findings. Only one car of the 16 exhibits a decrease in fuel economy on the FTP relative to the UC (a 1982 GM Corvette) while all of the others experience an increase, with the greatest being over 14%.

Rather than being random variation, this range of fuel economy impacts are directly related to the power of the cars, more specifically to the horsepower/curb weight (HP/WT) ratio. The HP/WT ratio was calculated for each car in the sample, and the fuel economy penalty was found to be related to the ratio. The results, presented in Figure 4-2 below, imply that for a powerful (HP/WT ratio over 50 HP per 1000 lbs.) car, the fuel economy penalty for aggressive urban driving is minimal, but for those cars with a lower HP/WT ratio, the penalty can be significant. For a typical family sedan whose HP/WT ratio is around 0.04, it appears that aggressive driving at city speeds causes a 6% fuel economy penalty.

Table 4.1. **Parameters for FTP and UC Driving Cycles**

	FTP (city)	UC
Average Speed (mph)	21.18	24.63
Maximum Speed (mph)	56.70	67.20
Average Acceleration (mph/sec)	0.89	1.15
Maximum Acceleration (mph/sec)	3.30	6.90
Maximum Deceleration (mph/sec)	-3.30	-8.80

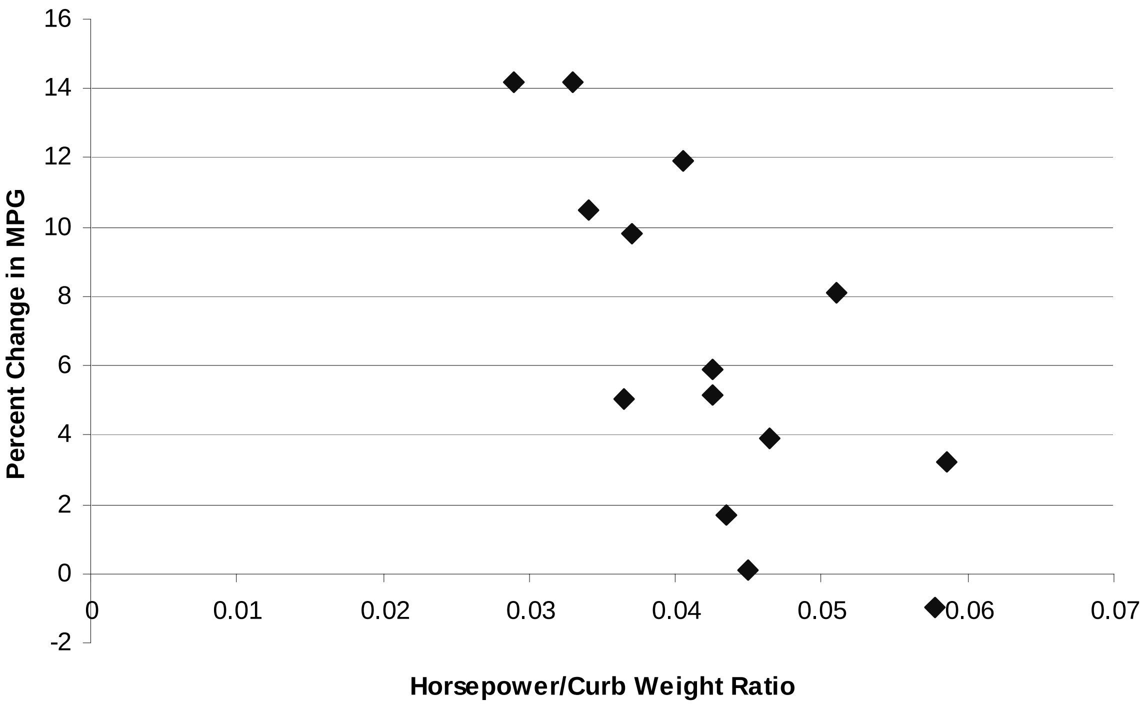
Figure 4.1. **Fuel Economy Penalty on the UC Test Cycle Relative to the FTP (City) Cycle**



Source: California Air Resources Board.

A second pair of driving cycles developed for emissions testing also facilitates an analysis of the fuel economy impacts of aggressive driving at higher speeds. The U.S. FTP highway cycle was developed in the early 1970s to be representative of driving on suburban roadways or expressways. The US06 cycle was developed in the mid-1990s by observing actual drivers and building a cycle to resemble the driving attributes of the 15% 'most aggressive' drivers, where 'aggressive driving' is characterised by high rates of acceleration, deceleration and high maximum and average speeds. The attributes of these two cycles are presented in Table 4-2.

Figure 4.2. **Fuel Economy Penalty as a Function of Horse Power to Weight Ratio**



Source: California Air Resources Board.

Table 4-2 shows that the US06 is 'more aggressive' than the FTP-HWY cycle on several measures, although the average speed is virtually identical:

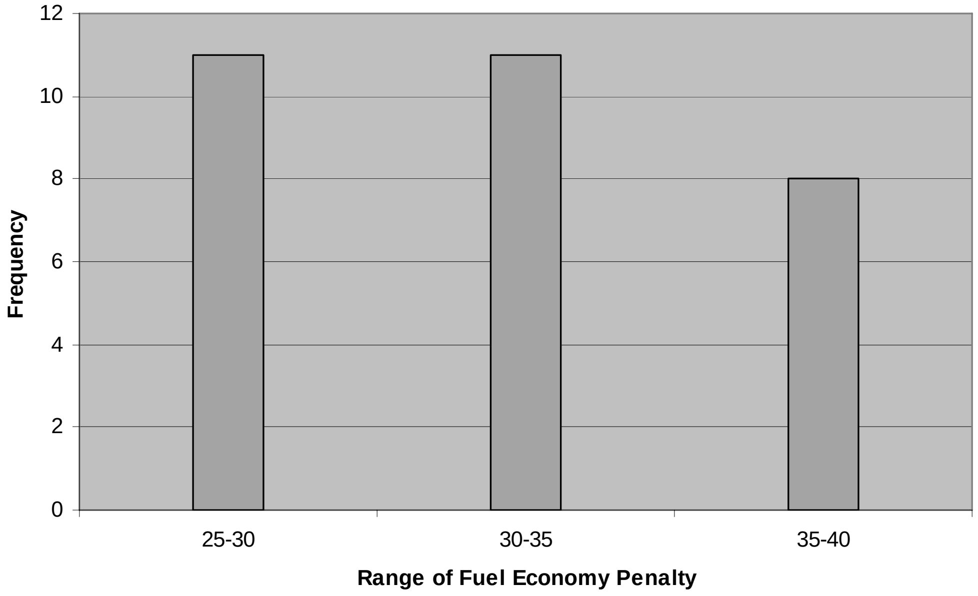
- The maximum speed is over 30% higher.

- The average acceleration rate is over 300% higher.
- Both the maximum acceleration and deceleration rates are over 100% higher.

Table 4.2. **Parameters for FTP (Highway) and US06 Driving Cycles**

	FTP (HWY)	US06
Average Speed (mph)	48.27	48.37
Maximum Speed (mph)	59.90	80.30
Average Acceleration (mph/sec)	0.384	1.383
Maximum Acceleration (mph/sec)	3.20	8.40
Maximum Deceleration (mph/sec)	-3.30	-6.90

Figure 4.3. **Fuel Economy Penalty US06 Vs FTP (Hwy)**



Source: Energy and Environmental Analysis Inc.

EPA tested a relatively large sample of cars on the US06 and FTP city driving cycles[14] but not the FTP highway cycle. The vehicle specifications (engine/transmission) were incomplete in the EPA data base and the FTP highway cycle "official" fuel economy value could not be directly determined. Instead, EEA matched the city cycle fuel economy value to the test car list value within 0.5 mpg and used the test car list based highway fuel economy as the appropriate value for each vehicle. This process resulted in matched US06 and FTP highway values for 30 cars. The observed changes between the measured US06 fuel economy and the official highway fuel economy test value for the sample are presented in Figure 4-3. All of the cars exhibit a large decrease in fuel economy, ranging from 25% to as high as 48% when driven on the US06 cycle, as compared to the fuel economy on the FTP highway.

5. TECHNOLOGIES TO IMPROVE FUEL ECONOMY OF GASOLINE VEHICLES

Substantial changes to vehicle technology have occurred since 1980, in response to the combined forces of fuel prices, regulation and consumer demand. While vehicle fuel economy increased rapidly in the early-to-mid-1980s in most OECD countries, there was a lengthy period (1985 to 1995) when new vehicle fuel economy was relatively flat. Since the mid-to late 1990s, fuel economy has increased in Europe and Japan, but has remained relatively constant in North America and Australia. Other vehicle attributes also changed significantly over the 1980-2002 time period. In the U.S., there has been a very large sales shift to “light trucks” of the compact van and sport-utility type; since 1980, compact van sales have increased from a few thousand to about 1.3 million per year, while sport utility vehicle sales have tripled to over three million per year in 2002. Similar trends are seen in Canada and Australia and, albeit to a substantially lesser degree, in many EU countries. Average vehicle horsepower has increased considerably in all OECD countries, rising by 25 to 50% since 1980. Vehicle weight for the same size (interior volume) vehicle has also increased due to the addition of luxury features. In particular, many consumer desired features such as more use of glass, anti-lock brakes, stability control and four-wheel drive, have played a major role in weight increases. The increase in the weight of power trains with performance is also significant. Passive safety features including new crash-test standards and air bag requirements have also had an impact, though are calculated to account for less than 30% of weight increases in Europe[15]. In spite of these changes, technology improvements have resulted in fuel economy improvement since 1980 in all OECD countries.

Broadly speaking, vehicle fuel economy improvements can be realized by:

- Reducing the tractive force requirements by reducing vehicle weight, drag and rolling resistance.
- Increasing the average efficiency of the engine over the drive cycle.
- Reducing internal friction losses.
- Reducing power consumption by accessories.
- Limiting engine speeds (by changing transmission ratios and through use of automatic gear changing).

A large number of technologies are available to reduce energy losses in each of the areas listed. Many have been already adopted since the 1980s in a majority of cars, while others are in the early stages of adoption. A significant number of technologies have yet to be adopted, or are currently available only in very small fraction of models, typically luxury cars. In general, technology utilization across the OECD countries does not vary dramatically, except for the use of diesel engines.

Weight reduction by the use of alternative materials is being widely utilized by all auto-manufacturers. However, as vehicle size and features increase, the weight reduction offered by alternative materials is offset by the weight increase from these factors. At constant size and features, however, weight reduction has been accomplished by (in decreasing order of market penetration):

- More extensive use of high strength low alloy (HSLA) steel in the body structure.
- Use of aluminium castings for the engine block, cylinder head and transmission case.
- Use of lightweight composite (plastic) materials in the vehicles interior.
- Use of composites to replace steel for body closures (bonnet, etc.) and the bumper.
- Replacing steel suspension members with aluminium forgings.
- Use of space frame or monocoque aluminium body-in-white.

While the use of HSLA, aluminium castings, and lightweight plastics in interiors is now common, very few vehicles use aluminium bodies. Aluminium bodies are currently only used in a few luxury car models, due to their high cost. Weight reduction has a larger benefit in fuel economy under stop-and-go driving conditions than at freeway speeds.

Drag reduction has also occurred in all OECD countries, with the drag co-efficient decreasing for most vehicles by 10 to 15% per decade. However, increases in frontal area have partially offset some of the benefits of drag reduction. In general, European cars have somewhat lower drag co-efficients, on average, than Japanese or North American models, possibly due to the relatively high speeds permitted on some European motorways. Over the next ten years, the historical drag reduction trend is expected to continue, but ultimately drag co-efficients will reach some practical limits below which their reduction will involve significant compromises in appearance or space utilization. These limits are likely to be approached by 2015-2020.

Tyre rolling resistance co-efficient has also decreased at about the same rate as the drag co-efficient, but this reduction has been partially offset by the trend of increased tyre performance in terms of traction and handling. The net fleet average decrease in rolling resistance co-efficient after accounting for performance improvements has not been large (about 5% per decade) in OECD countries. Tyre rolling resistance at constant tyre properties can be reduced by new formulations of rubber and new belt materials that reduce hysteresis losses, as well as by improvements of the design of the tread and side-wall.

As noted, the net reductions in tractive force have not been large in spite of the introduction weight, drag and tyre rolling resistance reduction technologies. This is due to increases in vehicle size, performance and features. Because the effects of the technology improvements are felt at all in-use conditions, they do not result in very significant changes in shortfall – improving performance on test and on-road conditions more or less equally. At the same time it is possible that the higher level of drag reduction in Europe contributes to some shortfall reduction at high speeds on expressways, reflected in overall shortfall figures to the extent that average driving speeds have increased.

Engine Technologies

Conventional (stoichiometric) operation gasoline engines continue to have the dominant market share of power plants sold in most OECD countries, although in some countries, the direct injection diesel has almost equalled the share of gasoline engines. However, the conventional gasoline engine has changed significantly since the early-1980s, and new technologies that can affect shortfall have been incorporated.

In general, engines from the early 1980s were mostly overhead cam (OHC)/two-valve type in the EU and Japan, and older overhead valve (OHV)/two-valve type in North American and Australia. Typically, OHC engines had specific output of 45 to 50 BHP/litre while OHV engines had specific output of 30 to 35 BHP/litre in the early 1980s. Since that time, specific output has increased greatly due to:

- Higher compression ratios.
- Improved intake and exhaust manifolds.
- Improved cylinder head and valve port design.
- Use of two or more intake valves and two exhaust valves.
- Reduced internal friction.
- Application of electronic injection and engine management systems.

Most engines in all OECD countries are now of the four-valve/OHC or double overhead cam (DOHC) design with specific power output in the range of 65 to 70 BHP/litre. The larger light trucks in North America continue to use two-valve engines in most models; GM is unique in still having a family of OHV two-valve engines, but these engines have been improved to produce 55 to 60 BHP/litre.

The 50 to 60% improvement in specific power has allowed modest performance increases while simultaneously reducing engine size in some models, and has allowed significant increases in power at constant engine size in other models. Fuel consumption during idle and braking are largely functions of engine displacement, and the fact that displacement has not increased suggest that idle and braking modes that contribute to shortfall have not worsened due to the power increase.

Variable valve control has the potential to significantly reduce light load pumping losses. The simpler technology of variable valve timing (VVT) by cam phasing has been widely adopted in luxury cars in Europe and North America, and in a large fraction of all cars in Japan; in fact, almost all Toyota models in 2003 had VVT. Variable valve lift and timing (VVLT) is less common; Honda is the only manufacturer to have a two step (or three-step) valve lift control in many of its models. A continuously variable lift system was recently introduced by BMW in its luxury 7-series cars. More exotic technologies actuate the valves without camshafts, using hydraulic or electric solenoids, but it is not clear if the additional cost is worth the marginal benefit in fuel economy relative to mechanical VVLT systems. Such systems will reduce shortfall in inner-city driving, but will increase shortfall in high speed or aggressive driving.

Cylinder cut-out also eliminates engine pumping loss, but is applicable primarily to V-8/V-12 engines, and possibly, to six-cylinder engines. Hence, it has much more market potential in North America and Australia than in the EU, where almost 80% of vehicles have four-cylinder engines. The effects on shortfall are similar to those for VVLT. At present, cylinder cut-out is used in a few luxury cars, but a large fraction of V-8s in North America are expected to utilize this technology by 2008.

Fuel injection and computer controlled electronic spark timing had already replaced the carburettor and distributor based ignition systems by the early 1990s. While fuel injection can reduce shortfall by reducing cold-start and acceleration enrichment, the computer control of fuel and spark timing allows closer "tailoring" of fuel economy to the test cycle. This raises the possibility of increased shortfall in off-cycle conditions.

Lean burn gasoline direct injection (GDI) engines have only recently entered the market in the EU and Japan, but had not yet been introduced in North America as of mid-2003. The GDI engine operates lean at light loads but reverts to stoichiometric operation (like a conventional gasoline engine) at high loads. At light loads, the GDI engine will have many of the advantages of a diesel engine (see below) in terms of reduced shortfall. However, the transition to stoichiometric operation at high loads makes the fuel economy quite sensitive to how the vehicle is driven. In particular, 'aggressive' driving will have a strong effect on shortfall with the GDI engine. Anecdotal reports from the EU with the first GDI engines introduced in the market in 2001/2002 have indicated that on-road fuel economy is substantially worse than advertised.

Transmission Technologies

In the early 1980s, most automatic transmissions had three to four forward speeds, while most manual transmissions had four or five forward speeds. Automatic transmissions were dominant in North America with a market penetration of about 76% while manual transmissions had the remainder. In Europe, the market share split between automatics and manuals was the opposite of the split in North America, with Japan and Australia having near equal market spilt of automatic and manual transmissions. Since the 1980s, market penetration of automatic transmissions has increased worldwide, with the U.S. market penetration at about 93% in 2002, and market penetration in Japan at about 80%.

A number of new technologies have been introduced for automatic transmissions. The number of forward speeds has increased so that the current market utilizes four or five speed automatics, while six speed transmissions have recently been introduced in luxury cars. Torque converters now utilize 'lock-up' of the hydraulic impeller and turbine at steady speeds to minimize slippage loss. Electronic control of shift points and lock-up is now common.

Manual transmissions have also increased the number of forward speeds from four/five to five/six. A new development is the “automated” manual transmission where the shift functions are performed automatically, and this transmission differs from the conventional automatic in not having a torque converter. While the elimination of the torque converter reduces losses, the shift quality is compromised, and many observers believe that such a system is only suited to sports cars or small cars where shift quality may not be a major issue.

Otherwise the technology of the manual transmission system has not changed significantly. The use of “shift indicator lights” (SIL), however, has become common in North America. The light provides a signal to the driver to shift up or down in a manner that would maximize fuel economy. European manufacturers do not use SIL since it cannot be used to determine gear shift points under the EC test procedure. In the U.S., the EPA allows its use on the certification test, but the results of this test are not used directly to report fuel economy. Rather, the test is conducted with and without the SIL and the SIL “use weighted” results are provided. SIL use rates are established by consumer surveys and the typical use rate is 40 to 50%. However, the low market penetration of manual transmissions in North America implies limited fuel consumption benefits from the use of the SIL.

A new type of transmission called the continuously variable transmission (CVT) has also been introduced in the marketplace in the late 1990s. The CVT is likely to replace the automatic transmission with gear steps especially in smaller cars with transverse, front-wheel drive. It is not clear if CVT will contribute to an increase or decrease in shortfall, since the transmission does not significantly change the operating characteristics under conditions most prone to causing shortfall.

Accessory Technologies

Improvements to vehicle accessories can reduce shortfall, since most accessories are not operated during the certification test. Typical engine driven accessories include the alternator, power steering pump, oil pump, water pump and air conditioner.

Alternators used in most vehicles are designed for low cost but have an efficiency of only 50 to 60%. During the certification test, the vehicle typically has all major electrically driven accessories (such as lights, fan and defroster) off, so that electrical loads are low. Improved alternator efficiency has only a small effect on the test fuel economy but potentially larger effects during on-road driving with additional electrical power demands. To date, very few vehicles employ efficient alternators, although this may change with the use of higher voltages (42 volts) or hybrid electric gasoline vehicles. (42V and hybrid systems are discussed below.)

Water and oil pumps are also designed primarily for low cost and durability but not for efficiency. These pumps operate continuously, independent of demand. Electrically driven water and oil pumps could be utilized to match output to cooling and lubrication demand, but because of the small benefits over the certification test these devices have not been adopted by the marketplace. Nevertheless there have been recent design improvements to water and oil pumps that make them more efficient.

The power steering pump operates continuously and is very wasteful when the steering is not being used to turn the vehicle. In this case, the test procedure reflects the worst case condition since the wheels are never turned during the test. Electric power steering (EPS) can provide “on-demand” power and reduce fuel consumption significantly (2 to 3%). However, shortfall will likely increase by a small amount if EPS is widely used due to the fact that the EPS will not be active during the test. EPS was first introduced into the marketplace in the late-1990s.

The air conditioner compressor used in many vehicles is a fixed displacement unit that is simply throttled for reducing the cooling rate. More efficient technologies include the variable displacement compressor, or the fixed displacement compressor with a cycling clutch. Typically, the air conditioner for a large car or sports utility vehicles absorbs 1.5 kW of power at idle RPM and up to 7.5 kW at high RPM. Advanced air conditioning systems using variable displacement, microprocessor controlled compressors, and recirculation of interior air, can reduce shaft power requirements by over 50%. Even more advanced heat pumps that are driven electrically can reduce loads by 70 to 75%, but the electrical load will require the use of higher voltage (42V) systems compared to the 12V system used today. Variable displacement compressors have penetrated the market in the U.S., but heat pumps have not yet been introduced. In the EU, air conditioning installation rates on new cars are quite low.

It is also possible to reduce air conditioner cooling demand by improved roof insulation and using specially tinted glass that acts as a barrier to infrared radiation. Roof mounted solar panels that provide electrical power to circulate cabin air when the vehicle is parked can act to reduce initial heat load on the air conditioner system. Such systems have been demonstrated but are not yet in production.

Design changes to the cooling system to improve engine warm-up from cold start have been demonstrated. One concept widely tested in the early 1990s was a “heat battery” that utilized a special canister containing a salt to store heat when the vehicle was shut down. Upon restart, the engine coolant is circulated through the heat battery to rapidly warm up to operating temperature. This technology can be useful in cold temperature/short trip situations to reduce shortfall. A simpler technology is the “dual cooling circuit” concept where the cylinder head and cylinder walls have separate cooling circuits, so that engine warm up time can be reduced significantly. Neither technology has been introduced in the marketplace as of 2003.

Hybrid Technologies

Combining an electric motor with the engine provides opportunities to maximize engine efficiency on both test cycle and on-road operating conditions. Typically, hybrid power trains can improve efficiency by the following means:

- Engine shutoff during idle/braking.
- Launch assist.
- Regenerative braking.
- Electric traction at low speeds.
- Transmission optimization.

The listing above is arranged in order of increasing electrical energy storage requirements (usually a battery) and increasing cost. Shutoff at idle and braking can be accomplished even with 12 volt electrical systems and existing batteries, although more advanced higher energy systems are preferred to keep accessories operating during engine shutoff. Higher levels of hybridization can increase system efficiency to obtain fuel saving of up to 50% on a city driving cycle (stop-and-go), but efficiency increases at highway speeds are substantially lower. The benefits of hybrid systems and the affect on shortfall can be complex. Two example cases are considered here: a ‘mild’ 42V hybrid system and a “full” hybrid operating at 300+V.

The 42V hybrid system improves fuel economy primarily by shutting the engine down during braking and idle. This factor can improve fuel economy by 7 to 9% on the city cycle but has no benefit for highway driving. However, the shut down feature is not initiated until the engine is fully warmed up, so that fuel economy is not improved in cold temperature/short trip operation. Depending on battery storage capacity, use of the air conditioner can also override the shutdown feature.

42V systems can also provide fuel economy benefits from increased electrical system efficiency (~1%), and from modest levels of braking energy recovery and launch assist (1 to 2%). These factors are not subject to the effects of cold temperature/short trip length or air conditioner use.

If the electric motor/generator is crankshaft mounted, it may be possible to improve the torque converter efficiency or eliminate the torque converter in an automatic transmission, which will provide some additional fuel economy benefit.

High voltage (300+V) systems are capable of providing much more electrical power. The full hybrid not only has all of the improvements associated with 42V systems but allows significant engine downsizing, electric traction at low speeds, and much more braking energy recovery. However, the system is not efficient at higher power demands, and the full hybrid may experience additional shortfall under aggressive driving conditions with attendant high power demand.

As noted in Chapter 2, several informal websites on hybrid vehicle fuel economy suggest a shortfall of 35 to 40%, which is much higher than conventional vehicles shortfall. It is possible that those who complain on the website of poor fuel economy drive more aggressively, and do not allow the system to operate at high efficiency.

Tyre Technology

Most drivers do not pay much attention to the impact of tyres on fuel economy. This is unfortunate as tyres are a significant factor in a car’s fuel economy. Tyres are directly responsible for about 15% to 25% of typical fuel consumption[16]. They also contribute to aerodynamic and inertia losses, resulting in a total amount of fuel consumption due to tyres that may approach 30%. It should be noted that this fraction varies significantly with speed and is highest at highway speeds. The wider and larger tyres that equip higher performance cars and most four wheel drive vehicles are associated with generally higher drag and inertia losses.

The tyre design contributes to vehicle fuel economy in several ways:

- The tyre has a given finite area that creates aerodynamic drag force.
- It has a mass that leads to inertia loss.
- It has rolling resistance that results from a combination of tyre-road friction and hysteresis. Hysteresis is a major component of a tyre's rolling resistance. As the tyre deforms, heat is dissipated in the various components of the tyre due to the visco-elastic nature of rubber.

The rolling resistance of tyres is usually measured by a laboratory test of a single tyre, not with a fuel consumption test on a car. Car tests for rolling resistance have also been defined but are not in general use. Despite the detailed specification of the tyre rolling resistance test procedures, the reality is that the variety of measurement methods being used with different measuring instruments under different circumstances results in significant variability of results. Many tyre manufacturers do not disclose test results on the rolling resistance co-efficient, citing this issue as one possible reason.

The relationship between rolling resistance and the resulting vehicle fuel economy has been examined in the literature. For passenger cars, the observed relationship is that a 5 to 7% reduction in rolling resistance produces a 1% increase in fuel economy. A report by the Goodyear technical center[17] in Luxembourg states that with the tyres available today, differences of 15% to 20% can be found between the rolling resistance of functionally similar tyres available in the market. This implies potential fuel savings of 2 to 4% by appropriate tyre choice. Goodyear's technical centre estimates that a 10% tyre weight reduction results in approximately 0.1% combined fuel economy gain. Lessening the tread depth and making the tyres narrower are all options that will increase fuel economy. The problem is that these options have a performance trade-off that may be unacceptable, including loss of wet grip and skid control reduction.

The 1990s saw the introduction and use of Silica (rubber with the addition of silicate) tyres. It is claimed that using Silica in treads to replace Carbon Black enables rolling resistance to be reduced without a corresponding reduction in wet grip or other tyre performance measures. The use of Silica in tread compounds can now be considered standard in Europe, but does not appear to have achieved the same level of market penetration in the U.S. Silica tyres were first introduced by Michelin, and their data shows significant reductions in rolling resistance of up to 20% relative to conventional tyres depending on Silica content.[18]

In March 2001, Goodyear announced a new tyre technology, BioTRED, that they claim has important environmental advantages as well as "remarkably lower rolling resistance" according to company literature. Goodyear claims that this technology lowers rolling resistance by 8% while increasing wet grip and also reducing the tyre weight by 5%. The tyre is being introduced in Europe currently.

An area where there is considerable disagreement between the environmental community and the tyre and auto industries is in the market for replacement tyres. The Natural Resources Defence Council[19] has reported that "The average rolling resistance of replacement tyres is about 20% higher than that of tyres that auto-manufacturers use on new vehicles." Marvin Bozarth, the executive director of the International Tyre and Rubber Association, states that this is not the case. He said that there may be a slight differential due to the fact that auto manufacturers are significantly stricter about tyres being exactly balanced, whereas tyre retailers may be less strict. Since manufacturers do not specify rolling resistance, there is no confirmation of the NRDC claim. However, there is acknowledgement in the industry that low-cost, private brand tyres for the replacement market do have significantly higher rolling resistance relative to new car tyres and to “brand-name” tyres.

Tyre Inflation

Every tyre comes with a recommended cold tyre inflation pressure, and if the tyre’s measured inflation pressure is below the recommended value, it is considered as under-inflated. In the Netherlands research for the Environment Ministry by TNO found 50% of all cars are driven on under-inflated tyres. In August 2001, the U.S. Department of Transportation’s National Highway Traffic Safety Administration (NHTSA) released the results of a survey[20] that showed many tyres on passenger vehicles are under-inflated. This survey, carried out at gas stations around the country, collected data on 11 530 passenger vehicles (cars, SUVs, vans and pickup trucks).

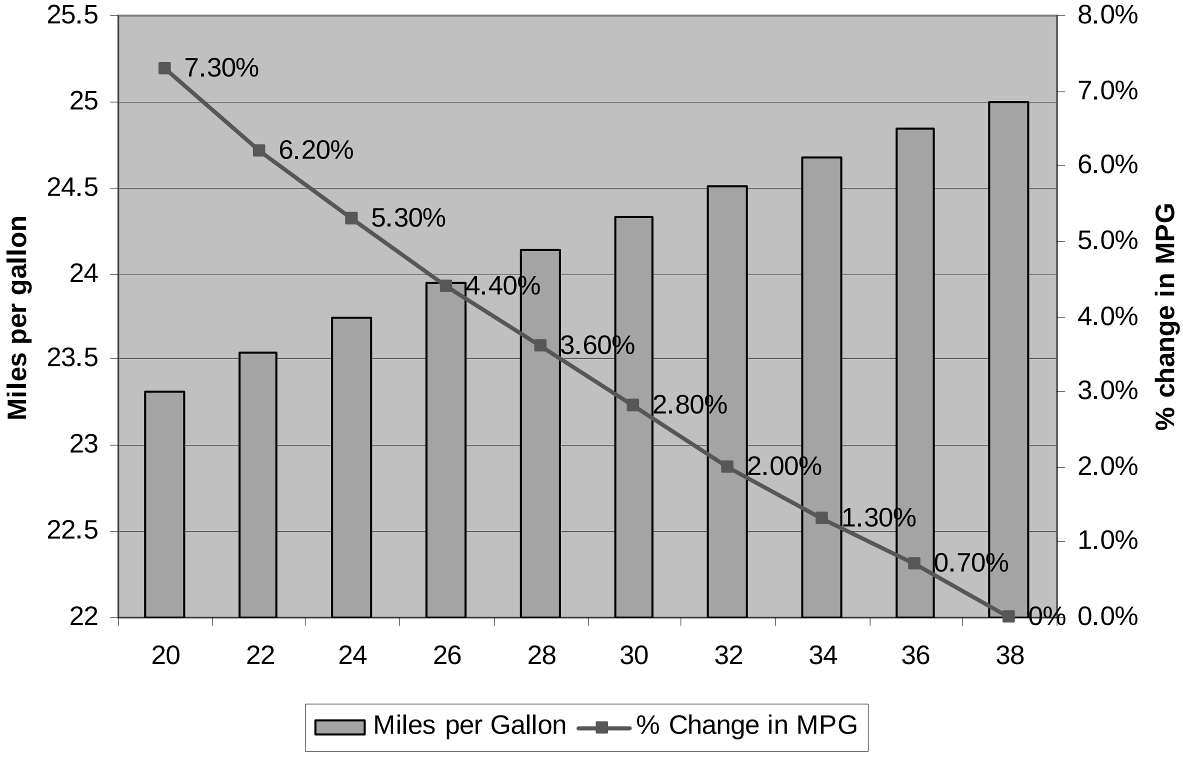
Table 5.1 lists the US survey’s findings. More than one in four of the passenger cars with P-metric tyres had at least one tyre under-inflated by 8 psi or more. For pickups, vans and SUVs with the P-metric tyres, almost one in three had at least one tyre under-inflated by 8 psi or more. The percentage of vans, SUVs, and pickup trucks with all four tyres under-inflated by 8 psi or more was twice that of cars with under-inflated tyres, as shown in the table below.

Table 5.1. **Results of tyre inflation survey: number of vehicles with 0 to 4 tyres under-inflated**

	No. of Tyres under-inflated by >8 PSI				
	0	**1**	**2**	**3**	**4**
Passenger Cars with P-metric tyres	73	14	7	3	3
Pickups, SUVs and Vans with P-metric Tyres	68	13	10	4	6

Figure 5.1, supplied by Goodyear, gives an indication of how under-inflated tyres translate into fuel economy impacts. This chart is for an example tyre with a recommended pressure of 38 psi, and it shows the fuel economy decline with under-inflation. The fuel economy decrease is approximately linear with under-inflation pressure, and inputs from tyre manufacturers suggest that the functional relationship is quite similar for tyres with slightly different recommended pressure. The majority of P-metric tyres have recommended inflation pressures of 28-34 psi. Taking 32 psi as a typical recommended inflation pressure, and assuming that the results displayed in Figure 5.1 are also typical, implies that 8 psi under-inflation results in a 3.3% decrease in MPG.

Figure 5.1. **Fuel Economy versus Inflation Pressure (38 to 20 PSI)**



Source: Goodyear.

New requirements for tyre pressure monitoring systems to indicate safety related problems from severely under-inflated tyres are being phased in over the next few years in most OECD countries (although the U.S. is currently the only country with a specific requirement). Such systems have the potential to be modified to indicate modest under-inflation for correction by the vehicle owner, but it is not clear if this will be incorporated voluntarily by manufacturers. Such an action could increase fuel economy for 30 to 40% of the fleet by 3 to 4%.

Tyre labelling for rolling resistance can provide similar benefits if consumers choose lower rolling resistance tyre brands with all other factors kept constant or near constant. None of the OECD countries require this information to be public, possibly due to opposition from some tyre manufacturers.

Fuel-efficient Lubricants

Engine oils serve several functions, including reducing friction, cooling the engine, limiting wear on the moving parts of the engine, and protecting against corrosion. It is primarily its effect on friction that impacts on fuel economy. Friction is an important cause of energy loss within the vehicle. Engine oils reduce friction in two ways:

- The oil separates opposing metal surfaces to prevent contact (*hydrodynamic lubrication*).
- Friction-modifying additives alter metal surfaces so friction forces are not as great when there is metal-to-metal contact (*boundary lubrication*).

Engine oils are categorized into grades such as 5W-20 or 10W-30. In the case of 5W-20 as an example, 5W refers to fluidity when cold (W = winter grade). The lower the number, the more fluid the oil at low temperatures, making cold starts easier. The 20 refers to fluidity when hot. The higher the number, the more viscous the oil at high temperatures and the better it protects when hot.

A second method of classifying oils is mineral versus synthetic. In conversations with lubricant manufacturers, their staff claimed that synthetic oils offer more durability, but no specific claims were made about fuel economy relative to a mineral oil of the same grade. Hence, synthetic and mineral oil of the same grade may not have significantly different effects on fuel economy, but the oil drain interval may be different.

The two major properties of engine oil that directly influence fuel economy are the oil's viscosity and the presence of friction modifying additives. The lowest possible viscosity results in the best fuel economy, but this choice is constrained by oil consumption and engine durability concerns. In recent years, the viscosity of engine oils has fallen significantly. In the 1970s and 1980s the most commonly used grades were SAE 10W-40 and 15W-40. These oils were gradually replaced by SAE 10W-30 and 5W-30 in light-duty engines during the 1980s. Today, the most commonly used factory fill oil in car and light-duty truck engines in all OECD countries is 5W-30, although some fraction of consumers continues to use 10W-30 or 10W-40 oil when the oil is changed. More recently, 5W-20 and 0W-20 oils have appeared in the market. 5W-20 oils are now used in many popular cars such as most model year 2000+ Honda cars and most Ford 2001+ vehicles as factory fill oil, while 0W-20 currently is used only in the new Honda Insight hybrid vehicle.

The issue of the manufacturer recommended oil is relevant because the new-car warranty only holds as long as the recommended maintenance procedures are followed, and this includes using the recommended oil. Conversations with lubricant manufacturers have confirmed that it is common practice for the "recommended" oil to be used until the warranty is over. Manufacturers are not explicit in disallowing the use of other oil grades, but are also not explicit about the issue of warranty continuation. Several major auto-manufacturers contacted by EEA conceded that, by and large, 5W-20 oil should be adequate for most modern (post-1995) cars and light trucks, but most manufacturers do not recommend it officially. However, manufacturers specifically cautioned against the use of 5W-20 oils in some high performance vehicles, vehicles subjected to heavy loads or trailer towing, and in very hot ambient conditions.

Fuel Economy Gains from Oils

There is a large volume of literature on the effect of oil properties on engine friction and on vehicle fuel economy. Much of the literature, however, focuses on specific oil properties and additives, and the literature on the relationship between commercially available oil formulations and vehicle fuel economy is more limited and generally available only for ambient temperatures in the range of 20±5°C. Most of the current literature compares the benefits of oils using 5W-30 as the reference base, since this oil is the factory fill oil for most light-duty vehicles since the early 1990s. Papers from the early-1980s have compared the performance of 5W-30 oils against 10W-30 and 10W-40 oil, and have found benefits in fuel economy in the 1.2 to 2.0% range. In almost all cases, the testing was conducted under standard conditions such as the U.S. EPA test or the American Society of Testing and Materials (ASTM) Sequence VI A test. In general, these tests underestimate the benefits of low viscosity oils to the consumer, as they do not involve testing at cold ambient where reduced viscosity benefits can be large. The benefits of 5W-30 oils over 10W-30/40 oils on more modern vehicles are in the same range, as confirmed in a 1995 paper by researchers Korcek and Nakada[21] (from Ford and Toyota, respectively), which summarizes the benefits of alternative oil formulations.

Korcek and Nakada also provide preliminary data on the benefits of 5W-20 and 0W-20 oils over 5W-30 oils. Data in the paper suggest that a fuel economy benefit of 1 to 2% is possible, although the range shown is large due to differences in friction modifiers between the different oil formulations. A more direct comparison of two commercially available oils with popular vehicles is found in the paper by Tseregounis and McMillan[22]. The paper indicates that 5W-20 engine oils demonstrate 1.0-2.2% (average 1.5%) fuel economy gains over the 5W-30 oils on several GM vehicles.

Most concerns with lower viscosity oils are associated with their effect on engine wear. Tanaka *et al*.[23] from Honda address these concerns. They study the impact of using a 0W-20 oil enhanced with a relatively common molybdenum based friction modifier. In their study, they compare the 0W-20 oil to a standard 5W-30 oil, with the same additive blends, both for fuel economy benefit and engine durability. They conducted tests on a Honda engine and a Honda vehicle, and found an impact of 1.5% on fuel economy with no significant difference on engine durability. At this moment, 0W-20 oil is only available from select retailers at a price of over $8 (Euro 7) per quart, as the Honda Insight is the only car for which this oil is explicitly recommended in the owner's manual.

Hoshino[24] et al., researchers from Toyota, found that the fuel economy of in-use engines can be improved by 1.5% on average using SAE 5W-20 oils containing friction modifying additives, when compared with the fuel economy achieved with conventional SAE 5W-30 oil without these additives. They also found that, in new engines, fuel economy can be improved with the same SAE 5W-20 oil by 3.5%. An improvement of more than 1.5% was retained to 10 000 kilometres (relative to a conventional SAE 5W-30 oil). These tests were done on a Toyota vehicle with a 2.2L, 4 cylinder, DOHC engine.

Lack of hard data on aftermarket oil purchase by consumers makes it difficult to estimate the benefits of mandatory use of 5W-20 oil where required. Although it is likely that 5W-20 oil is used during oil change for a significant fraction of cars where it is the factory fill oil, sales of 5W-30 oil and 10W-30 (even 10W-40) oil is still quite large, according to industry sources. However, oil changes may be preformed in a variety of locations and affecting oil choice may not be easy. Branding of oils as “fuel efficient” is already in place in most OECD countries. In addition, fuel savings are generally in the 1 to 1.5% range for the affected population, but fuel savings should be larger under cold conditions. Improved information especially under cold ambient conditions of 0°C or lower may be particularly useful in nations such as Canada and Sweden, where very cold temperatures are encountered.

Headlights and Daytime Running Lights

The use of vehicle headlights during the day for road safety reasons is spreading in numerous countries, either as a voluntary or a mandatory measure. It is now widely acknowledged to be an important measure to improve safety, attributed with decreases of 5% or more in crashes, injuries and fatalities. Some countries, such as Canada, Ireland, Hungary and all the Scandinavian countries require headlights to be used at all times. Some countries have set an obligation to use them in the winter period (Poland, Israel). The European Union and a number of its member states are considering similar action. The Netherlands, Austria and Switzerland are recommending the use of headlights during daytime on a voluntary basis. France is experimenting with this for a six month period finishing in June 2005.

Two main technical solutions exist to provide light during the day: one is to simply use the regular low beams (also called “dipped” headlights) which means that the device has to be switched on manually; the other is for the to be equipped with automatically switched on lights. The later solution is called “Daytime Running Lights” (DRLs). These lights are meant to produce a gentle luminescence that assures visibility without excessive glare for on-coming traffic.

DRLs can consist of any of the following:

- The use of the low beams which would simply be automatically switched on with the engine, sometimes with a lowering of voltage to avoid glare,

- The use of the regular high beams (also called headlamps on full beam) automatically switched on with the engine, and in all cases provided with lower voltage to prevent glare.

- Specific headlights dedicated to the daytime use, also switched on automatically.

Note that the two former approaches can be easily implemented on existing cars as they use the existing lighting facilities. For all three the manual switch to regular night time head light use overtakes the DRLs; the tail lights are switched off during DRL daytime operation.

For automobiles, the systematic daytime use of regular low beams at normal voltage is responsible for an estimated average additional fuel use of 1-2% on a yearly basis. On the other hand, DRLs, provided they are either specific devices or powered at lower voltage can reduce this energy use by about half.

Both in America and in Europe, the fuel economy tests for new cars do not include electrical equipment that can be switched on or off (e.g. air-conditioning, standard headlights and other lighting, stereo). So the use of regular low beams would not impact the tests results and there is no incentive in the test for manufacturers to provide more efficient lights. In contrast, the original equipment of cars with DRLs could provide such an incentive, as they are automatically switched on with the engine.

In Canada, it is mandatory since 1989 both for drivers to switch on the lights during daytime (if not equipped with DRLs), and for car manufacturers to equip the new vehicles with DRLs. Additionally, these DRLs have to comply with the SAE J2087 standard, which implies that they use a lower wattage than conventional headlights and hence consume about half as much electricity in use than regular headlights. This Canadian policy provides a sound trade-off, allowing the implementation of a safety measure while reducing the induced additional fuel use and CO_2 emission.

In the United States, the J2087 standard is implemented on a voluntary basis; car manufacturers may equip their new vehicles with DRLs but they do not have to. As of 2004, few new cars on the market are so equipped.

Regulation 87 under the UN/ECE 1957 Geneva agreement on vehicle standards is a similar regulation that has been adopted by a number of countries in Europe (including all EU countries), in the Middle East and in Asia. This implies that the manufacturers are allowed to introduce DRL equipped new cars in these countries, and in particular on the European Union’s internal market. But no standard production models have as yet been introduced, at least not EU-wide. This means that most of the cars in the Scandinavian countries or in Ireland, where daytime headlamps use is mandatory, are running with regular low beams on, which is a very inefficient solution regarding energy use.

With today’s lighting technologies, DRL efficiency could be much higher. For example, use of white LEDs (luminescent electric diodes) could reduce energy use significantly beyond the current average DRLs used in Canadian vehicles. Red LEDs are already used for tail and stop lamps in a number of existing models of cars, which provides good evidence that white LEDs could be used as front lamps during daytime. Standards could therefore be tightened, for example Canada’s 1989 specification.

Increased use of LEDs for DRLs could potentially yield valuable spin-off benefits of greater LED use in other applications, including:

- Other uses in transport (tail and stop lights, direction indicators).
- Regular headlights and fog lights.
- Greater use in building lighting.

Insufficient data was available on the incremental fuel economy benefits and costs of the different technologies to warrant including headlights in our overall estimates and comparative tables in this report. But this is an area that deserves further attention.

Fuel-saving Driver Support Devices

There are a number of technologies that provide feedback to the driver or directly control the vehicle and thus give fuel economy benefits[25]. Some have been designed to provide visual or audible aids to the driver to encourage less aggressive driving, and encourage driving in a manner to maximize fuel economy. These include:

- RPM gauges marked to show regions of engine speed for good fuel economy.
- Display of fuel economy in miles per gallon or km/litre as computed by the vehicle electronic control unit (on-board computer), either as an average or as a real-time instantaneous calculation.
- Shift indicator light (SIL), indicating the optimum point to shift gears, usually based on engine RPM, or dashboard lights to indicate fuel inefficient driving modes.
- Engine load (vacuum) indicators (econometers).
- (Adaptive) cruise control.

Most of these devices are already available in many vehicle models, and on-board diagnostics/service indicators are required for all light-duty vehicles in the U.S. and Canada. The fuel economy computer with electronic display is available as an option in a significant number of cars in Europe and the U.S. Hybrid vehicle models in the market today (from Toyota and Honda) have both numeric and graphical displays of instantaneous fuel economy, and these hybrid cars appeal to customers who want to maximise fuel economy. The SIL option may be particularly useful for Europe where the majority of vehicles are equipped with manual transmissions. Fuel economy benefits from the SIL can be in the 5 to 20% range[26] and proper shifting may account for a significant portion of the observed benefits of driver training in the Netherlands and Sweden. In addition to feedback devices, direct control technologies include cruise control, automated manual transmissions and speed or revolution limiters. Cruise control of the fixed speed variety is common in most North American vehicles, but adaptive cruise control is only now entering the market in luxury cars.

The fuel-saving effects of such devices are known from a number of demonstration projects and field tests carried out in the Netherlands since 1990. These included tests with econometers, eco-revolution meters, on-board computers, cruise controls, fuel consumption meters and speed and revolution limiters. Without any kind of ECO-DRIVING courses for the drivers (see chapter 2) these devices saved up to 5% fuel *on average*. Some of the drivers obtained no reduction in fuel-consumption, while others achieved reductions in fuel-consumption of well over 10%. Three conclusions could be drawn from the results:

- Equipping a fleet of cars with fuel-saving in-car devices improves their fuel consumption 5% on average.
- The fuel-savings with in-car devices are substantially higher in combination with ECO-DRIVING courses, about 10% on average.

- In order to be effective, the functionality of the in-car device has to meet certain criteria with respect to display and operability.

Due to these positive test results, the government of the Netherlands implemented a new car tax deduction to stimulate the fitting and use of fuel-saving in-car devices in newly sold passenger cars in May 2001. The sales tax credits stimulate auto manufacturers and importers to offer the devices as a standard accessory either without added costs or with reduced costs for the consumer. Current data from the Netherlands organisation of car importers show that approximately 75% of the new cars sold in the Netherlands in late 2002 were equipped with fuel-saving in-car devices, i.e. an on-board computer (with feedback on current fuel-consumption) or cruise control, or both. The percentage in neighbouring countries that do not have similar sales tax credits is about 25-35.

Moreover, a field experiment in 2000 demonstrated that car drivers can obtain even more impressive fuel savings when driving with a sophisticated tool that gives detailed advice on their driving behaviour during the trip, based on engine management data, including advice on when to shift gears. This fuel-economy support tool, which is a variation of the Shift Indicator Light (SIL), calculates optimal driving behaviour for minimum fuel consumption in real traffic. It gives feedback information to induce drivers to come close to this optimal driving style. The tool enabled drivers to reduce fuel consumption by 11% on average compared to normal driving. In the urban section of the route drivers reduced fuel consumption 20% compared to normal driving. Analysis of the data collected showed that the drivers kept learning during the test how to improve driving behaviour in order to minimise fuel consumption. This self-learning element of in-car feedback devices means that even further fuel savings may be expected over a longer period. Assisted by the fuel-economy support tool, participants drove significantly more often in the appropriate gear, mainly 5th gear. In addition, participants turned off the engine more often when idling, anticipated traffic conditions better and drove more smoothly.

While there is no question that these devices can save fuel[27], it is not clear how much attention vehicle owners will pay to the feedback devices without training (see above). Even without training, however, many of these low cost devices will be useful in motivating at least a minority of drivers to drive better. While drivers of manual transmission vehicles will benefit most from driver training, training may also prove valuable for drivers of hybrid vehicles, since driving style appears to have a significant impact on the actual on-road fuel economy of these vehicles. In North America and Japan, driver training programs targeted at hybrid owners may be especially valuable. It may also be valuable to add hybrids to training programs for all young drivers, in part to make them aware of the differences and fuel-economy benefits of hybrid vehicles.

Separately, navigation systems and real time congestion indicators have become possible with telematics and position devices. Navigation systems can provide more direct routes and prevent drivers from getting lost, although the effects of these systems are obviously very location and driver dependent. Congestion avoidance can help smoother traffic flow, but only if alternative un-congested routes are available. If all major roads are operating near capacity in an urban area, then congestion in one route will simply spill over to other routes.

CHAPTER SUMMARY

A wide variety of new technologies have been adopted in cars since the 1980s, and a majority of them have little or no effect on shortfall. Some technologies, notably those using electronic engine management, can increase shortfall by tailoring technology operation to the test cycle. Other technologies, such as diesel engines and, possibly, gasoline direct injection engines, could reduce shortfall under many operating conditions.

Table 5.2 provides a listing of most technologies that have been utilized widely in production vehicles in OECD countries. The table shows the test fuel economy benefit obtained on the USFTP or new European cycle and reflects the average benefit on the combined city and highway cycles. The values shown are derived from several studies on fuel economy conducted by EEA for the U.S. Department of Energy (DOE). The directional effect of the technologies on shortfall (reduction or increase) is provided for the four conditions identified in Chapter 3 as making the most significant contributions to shortfall. In this context ‘urban operation’ denotes mostly (>80%) city driving, while ‘highway operation’ denotes driving mostly at speeds in excess of 40 mph (65 kph). As can be seen, most production technologies do not influence shortfall in any significant way, while a handful of technologies can have a sizeable influence. It should also be noted that studies cited in the literature review (Section 2) have identified manufacturer specific calibration strategies as having a significant influence on shortfall, but this is not specific to any technology apart from electronic engine management.

A number of technologies aimed at improving fuel economy in off-test cycle conditions have not penetrated the market. These technologies include:

- Electrically driven oil and water pumps.
- Efficient alternators.
- Efficient air conditioners.
- Fast warm-up technologies.
- Use of fuel-efficient oils.
- Aids to improve driving habits.
- Idle-off and 42V electrical systems.
- Adaptive cruise control.
- Efficient air conditioners and heat pumps.

The reason that such technologies are not included in most vehicles is partially due to the limited benefit recorded on the official fuel economy test cycles. Table 5.3 provides a listing of these technologies and their effects on shortfall using a format similar to Table 5.2.

Tyres and oil are replaced periodically over a vehicle’s life and the replacement market is not well optimized for fuel economy. No tyre rolling resistance information is available in most OECD countries, although manufacturers acknowledge differences of up to 20% in rolling resistance between functionally similar tyres of different brands. Increased monitoring of tyre pressure could yield some fuel savings; it should be possible to adapt tyre safety related pressure monitoring systems to provide information on moderate under-inflation as well. Data on the type of oil actually used in the replacement market is limited, but small benefits in fuel economy may be realized if the market for fuel efficient replacement oil is optimized.

Aggressive driving is a major factor contributing to shortfall. The trend to more powerful cars will, however, reduce the impact of aggressive driving on shortfall, but will not eliminate it, especially in high speed driving conditions. A number of technological aids to assist the driver to drive in a more fuel efficient manner are available, but consumer motivation to follow the aids is not clear. The literature review shows that real world gains of 5 to 10% in fuel economy are possible, but widespread consumer acceptance of behavioural change has not been established.

Maintenance actions, outside of tyre pressure monitoring and replacement tyre and oil choice related issues, do not now have much impact on shortfall. This is largely because electronic engine controls have made tampering and maladjustment difficult to impossible, while emission inspections in most OECD countries provide strong incentive for at least yearly/biennial vehicle maintenance. After-sales replacement of electronic engine management systems to enhance performance may, however, be a source for concern.

Table 5.2. **Effect of Production Technologies on Test Fuel Economy and Shortfall**

Technology	**Test FE Benefit (%) (City/Highway Average)**	**Effect on Shortfall**				
		Cold Temperature	**Short Trips**	**Aggressive Driving**	**Urban Operation**	**Highway Operation**
Weight Reduction (5 to 10%)	3.5 to 7	-	-	-	Small R	-
Drag Reduction (10 to 20%)	2 to 4	-	-	-	-	Small R
Rolling Resistance	2 to 4	-	-	-	-	-
Engine Downsize + Increase Specific Output	2 to 4	-	-	-	-	-
Higher Compression ratio	1 to 2	-	-	-	-	-
VVT	1.5 to 2.5	-	-	-	-	-
VVLT	5 to 7	-	-	I	-	-
Cylinder Cut-Out	6 to 8	-	-	I	-	-
DI Diesel Engines	35 to 40	R	R	-	R	-
Gasoline Direct Injection	12 to 15	I	R	I	R	-
6-/5-Speed Automatic	2.5 to 5	-	-	-	-	R
CVT	5 to 7	-	-	-	-	-
Shift Indicator Light	3 to 5	-	-	R	R	-
Efficient Alternator	0.5 to 1	R	-	-	-	-
Electric Oil/Water Pump	0.5 to 1	R	R	-	-	-
Electric Power Steering	2.0 to 3.0	-	-	-	I	-
Mild-Hybrid (42V)	5 to 7	I	-	-	R	-
Full Hybrid	30 to 50	I	I	I	R	I
Engine Friction Reduction	2 to 4	-	-	-	-	-
5W-20 Oil	0.5 to 1	R	R	-	-	-
Electronic Fuel Injection	1 to 1.5	R	-	I?	-	-
Electronic Transmission Control	1 to 2	-	-	I	-	-

Notes: R: reduces shortfall; I: increases shortfall; Fuel economy benefits of technologies are not necessarily additive for many combinations.

Table 5.3. **Effect of Other (Currently Non-Production) Technologies on Test Fuel Economy and Shortfall**

Technology	Test FE Benefit (%) (City/Highway Average)	Effect on Shortfall				
		Cold Temperature	Short Trips	Aggressive Driving	Urban Operation	Highway Operation
Efficient Alternator	~0.5	R	R	-	-	-
Electric Oil Pump	~0.5	R	-	-	-	-
Electric Water Pump	~0.5	R	-	-	-	R
Heat Battery	~1.0	R	-	-	-	-
Aftermarket Fuel Efficient Oils	N/A	R	-	-	-	-
Driving Aids	N/A	-	-	R	R	R
Instantaneous fuel consumption read out (on-board computer)	N/A	R	R	R	R	R
Adaptive Cruise Control	N/A	-	-	R	-	R
Idle Off	3 to 5	I	-	-	R	-
Efficient Air Conditioner or Heat Pump	0	-	R	-	-	-

Notes: R: Notes: R: reduces shortfall; I: increase shortfall.

6. IMPROVING THE FUEL ECONOMY OF DIESEL VEHICLES

Diesel powered light-duty vehicles have been available for many decades, but their share of the market has increased rapidly only since about 1980. Light-duty diesel vehicles have become very popular in Europe and their market share has increased from a little over 10% in 1980 to 43% in 2003. In some countries in Europe such as France and Austria, diesel powered light-duty vehicles account for over half of all light–duty vehicles. In North America, however, diesel powered light-duty vehicles account for less then 0.5% of the total market. These vehicles enjoyed a brief burst of popularity in the 1979-1984 period, but in 2003 only one manufacturer (VW) offered diesel light-duty vehicles in North America. The situation is similar in Japan for cars, but most light-duty trucks in Japan and Asia are diesel powered. Of course, diesel engines dominate the heavy-duty truck market (over four tons gross vehicle weight) in all developed country markets.

Due to the diesels’ unpopularity in North America, little systematic work has been done to examine diesel vehicle shortfall, and to examine the effect of technology improvements on diesel engine fuel economy in ‘off-cycle” conditions. The analysis presented in this section is largely based on engineering analysis and the opinion of diesel engine experts in the automotive industry. Hence, the results presented here should be treated as preliminary estimates to be confirmed by actual testing.

The Benefits of Diesel

The major advantage of the diesel engine over the gasoline engine is its relative fuel economy. Its disadvantages are higher NOx emissions (5 to 10 times those of modern gasoline engines) and higher particulate emissions (although effective particle traps are now available on some cars). Diesel engines are more fuel efficient than gasoline (or spark ignited) engines for two reasons. First, the diesel cycle requires that fuel ignite spontaneously upon contact with hot compressed air. Hence, diesel engines employ high compression ratios of 16:1 to 20:1, which leads to high engine efficiency. Gasoline engines cannot employ such high compression ratios because the combustion process requires external ignition of a pre-compressed fuel-air mixture; the octane number of the fuel limits the compression ratio to about 10:1 for an engine using regular gasoline. Second, the power output of the diesel engine is controlled by regulating the amount of fuel per combustion event while the air inducted is unthrottled. In contrast, gasoline engines require the intake air to be throttled to control load, while keeping the air-fuel ratio constant. The throttling of intake air leads to pumping losses that increase at light loads (typical in city driving) in a gasoline engine. Such losses are absent in the diesel, and its fuel economy benefit under light load conditions over a gasoline engine is quite large.

On the negative side, diesel engines have much higher internal mechanical friction because of the need to seal the cylinder against high pressures. The high compression ratio and combustion process also lead to higher engine weight relative to a similar displacement gasoline engine, as well as reduced specific output and increased noise and vibration. These last three factors of reduced power, increased noise and higher vibration were often blamed for the lack of widespread acceptance of the diesel in North America, where the value of the diesels' enhanced fuel economy has been low.

The latest designs of light-duty diesel engines marketed in Europe provide significant improvements in virtually all of the characteristics of interest. Most of the development in diesel engines is centred in Europe; in Japan there are virtually no diesel engine passenger cars. In the U.S., Navistar, DDC and Cummins have displayed advanced prototype V-6 diesel engines in 2003 for use in light-trucks.

Until 1991, most diesel powered passenger cars and light trucks were all of the indirect injection (IDI) type, where fuel is sprayed into a prechamber, partially mixed and combusted with air before mixing and further combustion takes place in the main combustion chamber. The prechamber design results in smoother combustion with less noise and lower NO_x emissions. However, heat transfer from the prechamber and pressure losses from the partially combusted gases as they flow through the small passages connecting the prechamber to the main combustion chamber result in reduced efficiency. In fact, the peak efficiency of an IDI diesel is comparable to or only slightly better than that of a modern spark ignition engine.

Direct injection (DI) systems avoid the heat and flow losses from the prechamber by injecting the fuel directly into the combustion chamber. The fuel injection system must be quite sophisticated, as it must be capable of injecting very little fuel during the ignition delay period, while providing highly atomized fuel and intensive mixing during the diffusion burning phase of combustion. Advancements in fuel injection technology and diesel combustion chamber design led to the introduction of passenger car DI diesels by Volkswagen in their Audi and VW model lines in the early 1990s, and by most other European manufacturers thereafter.

Turbo charging has also been found to be particularly effective in combination with diesel engines as the intake air is unthrottled. All new DI diesel engines are turbocharged and many feature intercoolers, which provide a cooler, denser charge to the engine. As a result, the specific power of diesel engines with turbo charging now exceeds the specific power output of naturally aspirated, 2valve per cylinder gasoline engines. Turbo charging and intercooling are quite costly

New Engine Performance

Several manufacturers have introduced a range of new diesel engines featuring common-rail or unit injector technology. Specifications for a small selection of gasoline and equivalent diesel engine powered vehicles are shown in Tables 6.1. and 6.2., for six-cylinder and four-cylinder diesels respectively. The luxury class markets do not appear to have a standard price premium for the diesel, for example the Mercedes S-class six-cylinder diesel is cheaper than the S-class V-6 gasoline model (although these are some option trim differences). The BMW and Audi comparisons indicate a diesel six-cylinder price premium of about Euro 1600. Price premiums for four-cylinder diesels are about Euro 1200, typically.

The fuel economy benefit of the DI diesel over an ‘equal performance’ gasoline engine is closely dependent on the engine model and axle ratios employed for the gasoline versus the diesel car. The older IDI diesels typically showed much smaller benefits on high speed cycles, whereas the newer DI diesels show only a modest reduction in benefits on the higher speed EUDC cycle relative to the very low speed ECE R15 cycle.

The reduced sensitivity of fuel economy benefit to speed suggests that the DI diesel benefit on the U.S. test may be quite similar to the average benefit recorded on the ECE + EUDC cycles. For the six-cylinder engines, fuel consumption benefits are reasonably consistent across models at 28±5% on the ECE cycle and 24±3% on the EUDC cycle. The four-cylinder comparisons in Table 6.2. show larger variations across models.

In summary, the advanced DI diesel appears to provide 25 to 28% fuel consumption reduction (equivalent to 33 to 39% fuel economy increase) on the test cycle when compared to an equivalent modern four-valve gasoline engine providing approximately equal performance. The benefit is higher at lower speeds and lower at high speeds (over 100 km/hr).

Diesel Vehicle Shortfall

Although recent tests in the EU have found large shortfall with large diesel engines, early studies of shortfall in the U.S. showed diesel vehicles had significantly less shortfall than gasoline vehicles of similar size and technology. As shown in Figure 2.1. of this report, diesels were found to have shortfall in the 5 to 8% range on the U.S. tests, although the sample size was about 100 vehicles each at 24 and 42 miles per gallon (corresponding to the GM V-8 and VW four-cylinder diesels). The reasons for the low diesel shortfall were attributed to:

- Reduced need for cold start enrichment at cold ambient temperatures, relative to gasoline engines.
- Lack of acceleration enrichment.
- Low idle fuel consumption relative to gasoline engines.

These factors would not have changed significantly in the last 20 years, although the gasoline engines' need for cold start and acceleration enrichment has declined due to the replacement of the carburettor by port fuel injection over this period. At the same time, diesel engine idle fuel consumption has declined further due to the conversion from indirect to direct injection.

Due to the inherently lower shortfall observed for diesel vehicles fuel economy in the early literature, there has not been much focus on examining the causes and the impact of on-road conditions on diesel vehicle shortfall. More research is warranted given the current rapid dieselisation of European passenger car fleets, and the indications of the small number of more recent tests in Europe.

Low Ambient Temperatures

As noted, short trips in combination with low ambient temperatures is one of the main causes of gasoline vehicle shortfall. Diesel engines require much less enrichment during cold start, and the typical level of excess fuel consumption at a 0°C cold start is only about 35 to 40% of the excess fuel used in a gasoline engine. As a result of this reduced enrichment, many of the "fast warm-up" technologies and electrically driven water pumps have only a minor effect on actual in-use diesel fuel economy.

Aggressive Driving

The effects of aggressive driving with a diesel powered vehicle depend on two factors: (1) acceleration-deceleration events and (2) absolute speed. In general, the lack of acceleration enrichment reduces the effects of "stop-go" driving on fuel economy, but energy lost in the brakes due to deceleration events will, of course, be identical to that in gasoline vehicles. However, if aggressive driving also involves "revving" the engine to a high RPM before gearshift, the impact on fuel economy is greater in diesel vehicles due to the higher internal engine friction in a diesel engine. Thus driver training, shift indicator lights and the other driving aids discussed above should have similar percentage benefits in fuel economy for diesel and gasoline vehicles.

The effect of vehicle speed on fuel economy is larger for diesel vehicles in comparison to its effect on gasoline vehicles. Even the test values indicate that the diesel engine's fuel economy benefit over a gasoline engine on the same vehicle is smaller on the high-speed test than on the low-speed city cycle. At 150 km/hr, the DI diesel's fuel consumption advantage is typically only 15 to 18%, as opposed to 25 to 28% on the city cycle. (This corresponds to a fuel economy advantage of 18 to 22% at high speeds compared to 33 to 39% at low speeds.) Hence, technologies to control maximum speed, such as mechanical or adaptive cruise control, are more beneficial on diesel, relative to gasoline vehicles.

Traffic Conditions

As with gasoline vehicles, operation in denser traffic under stop-and-go conditions will reduce diesel vehicle fuel economy, while operation in light traffic at moderate highway speeds will increase fuel economy. Nevertheless, diesel fuel economy is less sensitive to the mix of traffic conditions than gasoline vehicle fuel economy. This is because in stop-and-go conditions, idle fuel consumption has a large effect on fuel economy. Diesel vehicles consume very little fuel at idle, and idle fuel consumption reduction relative to a gasoline vehicles is on the order of 40 to 45%. Hence, fuel economy shortfall due to operation in dense traffic is reduced.

In this context, the effect of "idle-off" technology is much smaller for the diesel. In typical city driving, a gasoline vehicle can obtain a fuel economy benefit of 8 to 10% from "idle-off", but the benefit is reduced to about 5% for a diesel. It should be noted that the first commercial "idle-off" technology introduction was on a VW diesel, but this was because VW was attempting to reach a very high fuel economy target. Due to the limited fuel economy benefit, the VW product was discontinued.

Increased operation in light traffic or highway conditions reduces shortfall for both gasoline and diesel vehicles, but in this case, the shortfall reduction is limited because diesel vehicles lose fuel economy advantages over gasoline vehicles at higher speeds. Of course, as speeds increase over 120 km/hr, diesel vehicle shortfall increases as discussed above.

Table 6.1. **Comparison of 2002 Vehicle Performance Six-Cylinder Engines**

	Mercedes E-Class		**Mercedes S-Class**		**Audi A-6**	
Model	**E280**	**E320D**	**S320**	**S320D**	**2.8L V-6**	**2.5L V6D**
Weight (kg)	1700	1760	1800	1905	1460	1565
HP	204	197	224	197	193	180
Torque (N-M @ RPM)	270 @3000	470 @1800	315 @3000	470 @1800	280 @3200	370 @1500
Acceleration (0 to 100)	9.5	8.8	8.2	8.5	83	8.8
City (L/100 km)	15.6	11.3 (27.6%)	17.1	11.4 (33.3%)	15.9	12.2 (23.3%)
EUDC (L/100 km)	7.9	5.9 (25.3%)	8.2	6.0 (26.8%)	7.8	6.1 (21.8%)

Table 6.2. **Comparison of 2002 Vehicle Performance Four-Cylinder Engines**

	Mercedes A Class		**VW Passat**		**Audi A-3**	
Model	**A160**	**A170D**	**1.8 G**	**1.9 TDI**	**1.8 G**	**1.9 TDI**
Weight (kg)	1040	1090	1289	1314	1160	1190
HP	102	90	125	110	125	110
Torque (N-M @ RPM)	150 @4000	180 @2000	168 @3500	235 @1900	168 @3500	235 @1900
Acceleration (0 to 100)	11.9	13.7	10.9	11.2	9.7	10.5
City (L/100 km)	10.3	6.2 (39.8%)	12.5	9.2 (26.4%)	11.8	6.7 (43.3%)
EUDC (L/100 km)	5.8	4.2 (27.6%)	7.2	5.4 (25%)	6.4	4.2 (38.2%)

Effects of Other Technologies

Broadly speaking, technologies that reduce engine loads will have similar effects on diesel or gasoline vehicle fuel economy in percentage terms. These technologies include vehicle weight and drag reduction, tyre rolling resistance reduction and accessory load reduction (efficient alternator, electric power steering, and improved water and oil pumps). However, the effect of improved engine oils can be larger for diesel engines since they have higher internal engine friction than gasoline engines. At the same time, improved oils have their most significant benefits during cold start, where the diesel fuel consumption penalty is not as large as that for a gasoline engine. Hence, the net fuel economy benefit of improved oils may be similar to that for gasoline engines.

7. TECHNOLOGY COSTS AND POLICIES TO PROMOTE TECHNOLOGIES THAT IMPROVE FUEL ECONOMY

The literature review and engineering analysis presented in the two previous sections of this report document a number of technologies “available” to reduce shortfall. The term “available” is used to indicate that no technical barrier exists for commercialization but the technology has seen only limited or no introduction yet in the market. Part of the reason for limited penetration is that auto-manufacturers are able to claim little or no fuel economy benefit on the official certification test. Another reason is that ambient, geographic and traffic conditions vary greatly between OECD countries and even within countries from region to region. Since the benefits of available technologies for reducing shortfall are often significant only under specific ambient/traffic conditions, manufacturers are often unwilling to standardize these technologies. It is not possible to find a “one size fits all” solution to the issue of technology under-utilization. Technologies most useful to Sweden or Canada could have limited value to consumers in southern France or southern U.S. Even the ranking of technologies by cost-effectiveness to produce a “supply curve” of available technology is not possible unless it is customised to specific sets of conditions.

One possible approach is to develop technology supply curves for classes of customers that share many common driving conditions whilst limiting the number of classes to a few, large enough to allow manufacturers to capture economies of scale. The previous analysis suggests four important distinctions (in a 2x2 matrix): cold or hot ambient conditions, and dense or light traffic conditions (corresponding typically to large city or small city/rural conditions). Although some technologies have benefits that fall across all four customer classes, most technologies discussed perform well only for one or two classes.

The class distinctions are somewhat subjective, but are defined as follows:

- Locations with cold ambient temperatures - where daily low ambient temperatures are below 10°C for over six months.

- Locations with hot ambient temperatures - where daily high temperatures exceed 25°C for over six months.

- Dense traffic conditions - with city-wide average speeds below 25 km/hr (16 mph).

- Light traffic conditions - with city-wide or rural average speeds in excess of 40 km/hr (25 mph), corresponding to freely flowing traffic.

There will be locations with temperate summer and winter conditions that would not belong to either of these ambient temperature categories, and locations with city-wide average speeds that fall between 25 and 40 km/hr and do not belong to either traffic category. Technology cost-effectiveness results for such locations will likely fall somewhere between the class specific supply curves.

Technology by Location Class

Some "technologies" such as driver training and instrumentation to reduce aggressive driving have benefits that are generally independent of location class, but other technology benefits are strongly dependent on both location class and frequency of use. Under these circumstances, a definitive "supply curve" in quantitative terms is difficult to define. In should be noted that the specifications of the baseline vehicle itself also influence the benefits derived from specific technologies.

Rather than a supply curve that might be easily misinterpreted, technology cost/benefit evaluations are presented below for each of the broad classes of ambient and traffic conditions identified. Each technology has an associated "payback" to the consumer in terms of fuel savings versus incremental cost. Naturally, the payback period depends on the annual driving distance, the baseline vehicle fuel consumption, fuel cost and in-use technology effectiveness. These factors are considered in the following analysis under two scenarios designed to be representative of high fuel cost locations, such as the EU, and low fuel cost locations such as the United States.

Table 7.1 provides a list of 13 technology options to reduce shortfall for gasoline vehicles. The technology cost, or more accurately the retail price equivalent, presented is an estimate of how much the retail price of an average vehicle would increase under competitive conditions if the technology were added to the vehicles. In this context, the retail prices in dollars or in Euros are nearly numerically identical due to higher taxes in Europe being offset by the higher current value of the Euro.

"Driver training" includes technologies to assist drivers to drive in a fuel efficient manner, such as tachometers marked to show efficient RPM ranges. The "cost" of driver training is the approximate cost of two to three one-hour training sessions in fuel efficient driving, although the cost of using a driving simulator, as used in the Netherlands, is much lower. For other technologies, the cost has been determined based on inputs from auto-manufacturers and Tier I suppliers to the auto industry.

The fuel economy benefits are expressed in percent increase in fuel economy (percent decrease in fuel consumption). This data is derived from limited test data on fuel economy effects cited in Chapter 3. For technologies specific to cold or hot ambient temperature (such as fast engine warm-up devices or efficient air conditioners), it is assumed that such ambient temperature are encountered 50% of the time in the specific locations; e.g., the air conditioner is operated 50% of annual miles travelled in locations with hot ambient temperatures.

As shown in Table 7.1, all of the benefits are typically small (in the range of 1 to 5%) with only three exceptions: for idle stop/start in dense traffic, driver training effects in light traffic, and adaptive cruise control in light traffic. The driver training effect assumes the maintenance of more constant speeds but does not assume a speed reduction. It should be noted that technology benefits are not additive; for example, adaptive cruise control performs a function similar to driver training, but has more limited use at city speeds since such systems cannot yet bring the vehicle to a full stop.

Table 7.1. **Costs and Average Fuel Economy Benefit Estimates for Technologies to Reduce Gasoline Vehicle Shortfall (%)**

Technology	Retail price (Euros or $)	Cold ambient		Hot ambient	
		Dense traffic	Light traffic	Dense traffic	Light traffic
Electric Water Pump	100 – 150	4	2	2	1
Efficient Alternators	40 – 60	2	1	1	0.5
Efficient Air Conditioners	80 – 120	0	0	3	1
Heat Pumps for Air Conditioning	200 – 300	0	0	5	2
Heat Battery	80 – 100	3	1	0	0
Dual Cooling Circuits	30 – 50	2	2	1	1
Idle Stop/Start (assumes 42V system)	300 – 400	4	0	8 *	0
Low Rolling Resistance Tyres	50 – 80	1	2	1	2
0W-5W/20 Oils	40 – 60	2	1	0.5	0.5
Tyres Inflation Monitor	30 – 40	1	1	1	1
Shift Indicator Light (manual trans.)	25 – 35	2	1	2	1
Driver Training	150 – 250	5	10	5	10
Adaptive Cruise Control	1 000 – 1 500	3	10	3	10

* With separate air conditioner drive.

Table 7.2 shows the technologies available to reduce diesel vehicles shortfall. As can be expected, the fuel economy benefits are smaller for technologies that deal with cold start and idle fuel consumption. The relatively small benefits for most technologies illustrate one difficulty in market acceptance – the fuel savings are barely noticeable to consumers who typically are not sensitive to small fuel economy variations of ±5%. Motivation for consumer action is limited due to the small absolute value of the fuel savings.

Technology Payback Period and Cost per Tonne for CO_2 Emission Reductions

One measure of technology cost/effectiveness is the time required (or miles driven) to pay for the technology cost from the fuel savings. This is a useful measure to understand consumers' willingness to purchase the technology (or for manufacturers to determine if it is worth it to consumers to put the technology on vehicles). Another measure is the cost effectiveness of the technology for reducing CO_2 emissions, taking into account both the cost of the technology and the fuel savings it provides; with the net cost (or savings) compared to the CO_2 emissions reductions provided. These two approaches are used below to estimate technology cost effectiveness for consumers and for society.

Table 7.2. **Costs and Average Fuel Economy Benefit Estimates for Technologies to Reduce Diesel Vehicle Shortfall** (%)

Technology	**Retail price (E or $)**	**Cold ambient**		**Hot ambient**	
		Dense traffic	**Light traffic**	**Dense traffic**	**Light traffic**
Electric Water Pump	100 – 150	2	1	1	0.5
Efficient Alternators	40 – 60	2	1	1	0.5
Efficient Air Conditioners	80 – 120	0	0	3	1.5
Heat Pumps for A/C	200 – 300	0	0	5	2.5
Heat Battery	80 – 100	1.5	0.5	0	0
Dual Cooling Circuits	30 – 50	1	1	0.5	0.5
Idle Stop/Start (assumes 42V system)	300 – 400	2	0	4 (with A/C drive)	0
Low Rolling Resistance Tyres	50 – 80	1	2	1	2
Low Friction/Viscosity Oil	40 – 60	1	0.5	0.5	0.5
Tyres Inflation Monitor	30 –40	1	1	1	1
Shift Indicator Light	25 – 35	2.5	1.5	2.5	1.5
Driver Training	150 – 250	5	15	5	15
Adaptive Cruise Control	1 000 – 1 500	3	15	3	15

Payback period is a function of local fuel prices, annual driving distances and baseline vehicle fuel economy (in this case actual average on-road fuel consumption per kilometre). Three cases are considered as examples of the range of fuel economy and fuel cost encountered among OECD countries. These are:

- Gasoline cost of $1.50 per gallon (about Euro 0.30 per litre), with a baseline (gasoline) vehicle achieving 27 mpg (8.7 l/100 km) driven 12 000 miles (19 200 km) annually (corresponding to average U.S. conditions and vehicles).

- Gasoline cost of Euro 0.90 per litre, with a baseline gasoline vehicle at 7.5 l/100 km (31.4 mpg) driven 15 000 km annually (corresponding to average European conditions and gasoline vehicles).

- Diesel fuel cost of Euro 0.75 per litre with a baseline diesel vehicle at 5.6 l/100 km driven 18 000 km annually (corresponding to average European conditions and diesel vehicles).

The above fuel economy values are "official" ratings and a real world shortfall of 20% in fuel consumption is assumed to compute annual fuel use. Under these conditions, the annual fuel cost is $ 800 in the first scenario (about €640), Euros 1 215 in the second, and Euros 907 in the third. Consumer surveys show that consumers expect simple payback within three years to invest in a technology.

For calculation of net CO_2 reduction costs, the same scenarios are considered but a different fuel cost assumption employed. In order to derive an estimate of total social cost for gasoline use, fuel taxes are excluded but fuel use over most of the vehicle life is considered, and discounted at a social discount rate of 3%. The fuel cost estimate used is $0.40 per litre, reflecting oil cost at $36/bbl, plus refining, transport and retailing costs. In a social cost analysis, external costs such as oil import dependency costs and environmental costs (in this case other than related to CO_2) should generally be included as well. However, these are not included here for two reasons: in order to keep the estimates conservative and avoid a discussion of the appropriate estimates to adopt; but if external costs were added, they would of course make the estimated value of fuel savings higher, and the cost estimates for reducing CO_2 emissions lower.[1]

This fuel cost assumption is applied to each of the three scenarios mentioned above, while the travel and fuel economy assumptions are kept the same. For valuing fuel savings from technologies, a 10 year fuel savings horizon is used, with a 3% social discount rate (such assumptions are unnecessary for calculating payback rates). Replacement costs for all technologies (including tyres and oils) over a 12-14 year average vehicle life is already factored into the technology cost estimates, so using a 10 year horizon on fuel savings is somewhat conservative.

Payback periods for the U.S. case are shown in Table 7.3 for the different technologies. Only dual cooling circuits for reducing cold start fuel consumption and the shift indicator light for urban drivers achieve a pay-back in less than three years. Driver training for improved high speed driving also meets this criterion, although the savings can be quite variable between different consumers.

Tyre inflation monitors in generally light traffic conditions appear marginally attractive to consumers. Several other technologies are marginally attractive in cold ambient conditions, with four year payback periods; efficient air conditioners also have four year payback in hot climates and dense traffic conditions; Though the data used here for the US (from the literature review) suggest that driver training is only likely to be cost-effective for light-traffic conditions, data from the Netherlands suggests that such programmes can be designed to be cost effective under all conditions.

In contrast to the relatively slow pay-back times and thus poor cost-effectiveness of most technologies from the point of view of consumers, from the point of view of society (and given the fuel cost assumptions described above), nearly all the technologies are quite cost-effective for gasoline vehicles in the US in at least some driving conditions. Many technologies in Table 7.4 show a negative cost. These can be considered "win-win" or "no-regrets" options for society. Dual cooling circuits, tyre inflation monitors, shift indicator lights, low-rolling-resistance tyres and driver training all show a negative cost in all four situations considered. For those technologies showing positive costs, those under $100 per tonne CO_2 might be considered modest-cost CO_2 reduction options, at least compared to many other policy options in the transport sector (which are commonly above $100/tonne, e.g. biofuels; see IEA 2004[30]).

Table 7.3. **Technology Payback Period (years) Gasoline Vehicle, US Fuel Price and Driving Assumptions**

Ambient	**Cold**		**Hot**	
Traffic	**Dense**	**Light**	**Dense**	**Light**
Electric Water Pump	3.91	7.81	7.81	15.63
Efficient Alternators	3.13	6.25	6.25	12.50
Efficient Air Conditioners	NA	NA	4.17	12.50
Heat Pumps for A/C	NA	NA	6.25	15.63
Heat Battery	4.17	8.33	25.00	NA
Dual Cooling Circuits	**2.50**	**2.50**	5.00	5.00
Idle Stop/Start (assumes 42V system)	21.88	NA	10.94	NA
Low Rolling Resistance Tyres	8.13	4.06	8.13	4.06
0W-5W/20 Oils	3.13	6.25	12.50	12.50
Tyres Inflation Monitors	4.38	4.38	4.38	4.38
Shift Indicator Light (manual trans.)	**1.88**	3.75	**1.88**	3.75
Driver Training	5.00	**2.50**	5.00	**2.50**
(Adaptive) Cruise Control	NA	52.08	NA	52.08

NA – no technology benefit under these conditions. Shaded cells: payback in under four years.

In the European context, with a regime of higher retail fuel prices, many technologies are cost-effective from the consumer's viewpoint, especially at cold temperatures. Under such ambient conditions, most technologies, except for idle stop and adaptive cruise control, are within the consumer payback period criterion of three years, as shown in Table 7.5. Under hot ambient conditions, the situation is less favourable. This is to be expected since the test procedure represents hot ambient conditions well, and cost effective technologies are likely to be already introduced as a result of market pressure.

Perhaps surprisingly, the estimates for cost-per-tonne of CO_2 abated under European conditions are not as low as for the U.S. This is because a) the same untaxed fuel price is assumed, and b) vehicles in Europe are driven less per year, and have better fuel economy, so use significantly less fuel. Thus the technology options considered have the potential to save less fuel in European vehicles than in US vehicles. Nonetheless, most technologies show CO_2 reduction costs below $100/tonne in both regions under at least some conditions. Only advanced cruise control fails to achieve costs of under $100/tonne under any conditions. Most technologies show negative costs in some situations (i.e. the value of their fuel savings is higher than their cost), and several continue to show a negative cost in all conditions.

Table 7.4. **CO_2 Cost per Tonne, Gasoline Vehicle, US Driving Assumptions**

Ambient Temperatures	**Cold**		**Hot**	
Traffic Conditions	**Dense**	**Light**	**Dense**	**Light**
Electric Water Pump	-$168	-$59	-$59	$158
Efficient Alternators	-$189	-$103	-$103	$71
Efficient Air Conditioners	NA	NA	-$160	$71
Heat Pumps for A/C	NA	NA	-$103	$158
Heat Battery	-$172	$36	NA	NA
Dual Cooling Circuits	-$207	-$207	-$137	-$137
Idle Stop/Start (assumes 42V system)	$28	NA	-$124	NA
Low Rolling Resistance Tyres	-$51	-$163	-$51	-$163
0W-5W/20 Oils	-$189	-$103	$71	$71
Tyres Inflation Monitors	-$155	-$155	-$155	-$155
Shift Indicator Light (manual trans.)	-$224	-$172	-$224	-$172
Driver Training	-$137	-$207	-$137	-$207
(Adaptive) Cruise Control	$1 170	$158	$1 170	$158

The diesel case is less conducive to technology introduction partly because of lower fuel cost savings and partly because the diesel uses less fuel during cold start. Nevertheless, as shown in Table 7.5., some technologies continue to be cost effective for the consumer under high speed driving conditions even in this case.

It should be noted that driver training programmes are cost effective for consumers under light traffic conditions for gasoline and diesel vehicles on the basis of data from the U.S. literature survey but that experience in Europe, and in the Netherlands particularly, shows that cost effective training programmes can be designed under all traffic conditions. In contrast, idle-stop, and adaptive cruise control are not cost-effective under any scenario. Given relatively long pay-back periods, most of these technologies probably will be marketed for reasons other than fuel savings.

Using the same social cost value for diesel fuel ($0.40 per litre) as gasoline, diesel technology impacts are typically as good or better than those for gasoline vehicles. Even advanced cruise control becomes cost effective (showing negative cost figures) in light-traffic conditions.

Table 7.5. **Technology Payback Period (years) Gasoline Vehicle, European Fuel Price and Driving Assumptions**

Ambient	**Cold**		**Hot**	
Traffic	**Dense**	**Light**	**Dense**	**Light**
Electric Water Pump	**2.57**	5.14	5.14	10.29
Efficient Alternators	**2.06**	4.12	4.12	8.23
Efficient Air Conditioners	NA	NA	**2.74**	8.23
Heat Pumps for A/C	NA	NA	4.12	10.29
Heat Battery	**2.74**	5.49	16.46	NA
Dual Cooling Circuits	**1.65**	**1.65**	**3.29**	**3.29**
Idle Stop/Start (assumes 42V system)	7.20	NA	**3.60**	NA
Low Rolling Resistance Tyres	5.35	**2.67**	5.35	**2.67**
0W-5W/20 Oils	**2.06**	4.12	8.23	8.23
Tyres Inflation Monitors	**2.88**	**2.88**	**2.88**	**2.88**
Shift Indicator Light (manual trans.)	**1.23**	**2.47**	**1.23**	**2.47**
Driver Training	**3.29**	**1.65**	**3.29**	**1.65**
(Adaptive) Cruise Control	NA	34.29	NA	34.29

NA – no technology benefit under these conditions.

Table 7.6. **CO_2 Cost per Tonne, Gasoline Vehicle, European Driving Assumptions**

Ambient Temperatures	**Cold**		**Hot**	
Traffic Conditions	**Dense**	**Light**	**Dense**	**Light**
Electric Water Pump	-$115	$46	$46	$369
Efficient Alternators	-$147	-$18	-$18	$240
Efficient Air Conditioners	NA	NA	-$104	$240
Heat Pumps for A/C	NA	NA	-$18	$369
Heat Battery	-$121	$188	NA	NA
Dual Cooling Circuits	-$173	-$173	-$70	-$70
Idle Stop/Start (assumes 42V system)	$176	NA	-$50	NA
Low Rolling Resistance Tyres	$59	-$108	$59	-$108
0W-5W/20 Oils	-$147	-$18	$240	$240
Tyres Inflation Monitor	-$95	-$95	-$95	-$95
Shift Indicator Light (manual trans.)	-$199	-$121	-$199	-$121
Driver Training	-$70	-$173	-$70	-$173
(Adaptive) Cruise Control	$1 875	$369	$1 875	$369

Table 7.7. **Technology Payback Period (years) Diesel Vehicle, European Fuel Price and Driving Assumptions**

Ambient	**Cold**		**Hot**	
Traffic	**Dense**	**Light**	**Dense**	**Light**
Electric Water Pump	6.89	13.78	13.78	27.56
Efficient Alternators	**2.76**	5.51	5.51	11.03
Efficient Air Conditioners	NA	NA	**3.68**	7.35
Heat Pumps for A/C	NA	NA	5.51	11.03
Heat Battery	14.70	29.40	NA	NA
Dual Cooling Circuits	4.42	4.42	8.82	8.82
Idle Stop/Start (assumes 42V system)	19.29	NA	9.65	NA
Low Rolling Resistance Tyres	7.17	**3.58**	7.17	3.58
0W-5W/20 Oils	5.51	11.03	11.03	11.03
Tyres Inflation Monitors	**3.86**	**3.86**	**3.86**	**3.86**
Shift Indicator Light (manual trans.)	**1.32**	**2.20**	**1.32**	**2.20**
Driver Training	**4.41**	**1.47**	**4.41**	**1.47**
(Adaptive) Cruise Control	NA	30.62	NA	30.62

Table 7.8. **CO_2 Cost per Tonne, Diesel Vehicle, European Driving Assumptions**

Ambient Temperatures	**Cold**		**Hot**	
Traffic Conditions	**Dense**	**Light**	**Dense**	**Light**
Electric Water Pump	-$159	$193	$193	$896
Efficient Alternators	-$370	-$229	-$229	$52
Efficient Air Conditioners	NA	NA	-$323	-$135
Heat Pumps for A/C	NA	NA	-$229	$52
Heat Battery	-$173	$502	NA	NA
Dual Cooling Circuits	-$285	-$285	-$60	-$60
Idle Stop/Start (assumes 42V system)	$474	NA	-$18	NA
Low Rolling Resistance Tyres	-$145	-$327	-$145	-$327
0W-5W/20 Oils	-$229	$52	$52	$52
Tyres Inflation Monitor	-$313	-$313	-$313	-$313
Shift Indicator Light (manual trans.)	-$443	-$398	-$443	-$398
Driver Training	-$285	-$435	-$285	-$435
(Adaptive) Cruise Control	$1 833	-$42	$1 833	-$42

Policies to Promote Technology Introduction

The consumer pay-back cost-effectiveness analysis provides a good illustration of why most of the 13 technologies identified have not made much headway in the free market. Even at fuel prices prevalent in the EU, few technologies are cost effective under all climatic and traffic conditions. The notable exceptions are the shift indicator light (SIL) and the dual cooling circuit system. However, given that many technologies show much better cost-effectiveness on a social (CO_2-reduction) rather than private basis, this suggests that government policies are needed to bring these technologies into greater use.

A number of technologies are particularly cost-effective from both consumer and societal viewpoints, primarily associated with gasoline vehicle shortfall reduction in cold ambient temperature and dense traffic conditions. These technologies are the electric water pump, energy efficient alternator, heat battery and 5W-20 oil. Under cold ambient dense traffic conditions, the combination of all these technologies could increase on-road fuel economy by 10+%, on average, or up to 20% during winter. These benefits could accrue in most urban locations in Northern Europe, Canada, the Northern U.S. and Northern Japan, and this appears to be a most promising area for policy intervention.

The SIL, applicable to manual transmissions, has already penetrated the U.S. market (which is quite small due to the low percentage of vehicles equipped with manual transmissions) but has not penetrated the EU due to the fact that manufacturers do not get any fuel economy credit on the test procedure for its adoption.

The dual cooling circuit system requires an engine cooling system redesign, and is likely to be introduced slowly as gasoline engines are updated or redesigned. The costs of this technology are primarily associated with capital investment in redesign, and best accomplished at the beginning of a product cycle for each engine model.

For diesel vehicles, methods to discourage high speed driving or high RPM shifting are the only cost-effective areas for intervention.

Policy measures to promote technologies typically include:

- Providing information to consumers.
- Command-and-control regulations.
- Financial incentive to consumers.
- Financial incentives to manufacturers.
- Voluntary agreements with manufacturers.

Information on cold temperature benefits of the technologies listed above would be a positive step but may provide only limited motivation to consumers. As noted, the net effect of any one technology is only few percent reduction on fuel consumption, and the cost-effectiveness is marginal (three to four years payback) from the consumers viewpoint. However, the technologies also have emission benefits at cold temperatures and the full cost of these systems need not be allocated to fuel savings alone. Many OECD countries have cold temperature emission limits that could be made more stringent to force adoption of these technologies. Modest fiscal incentives to manufacturers in the range of Euro 100 (or $100) per vehicle to reduce fuel consumption under cold ambient and low average speed conditions could promote their use in specific locations.

Driver training is cost-effective if drivers continue to follow the procedures subsequently. Promoting it is a particularly attractive policy measure because “ECO-DRIVING” does not only save fuel and reduce CO_2 emissions but also reduces other emissions (CO, HC, NOx, soot and other particles), traffic noise, accidents and damage and wear-and-tear to vehicles. The calculated cost effectiveness of the Netherlands ECO-DRIVING programme is €8 per ton CO_2 emission avoided.

Government subsidized training programs appear to be the only method to provide the required training. Such programs should be instituted along with publicity about the programs, and subsequent popularization with fuel efficient driving contests, etc.

It is difficult to estimate how training will affect the driving habits of the majority of drivers who (at least currently) do not appear to be motivated to learn and use efficient driving techniques. The Netherlands government argues that standard equipment of all new cars with fuel-saving in-car devices is the only way to address and influence the millions of licensed European drivers who are accustomed to the “old” way of driving (at too high RPM levels in too low gears for modern engines). As developing sufficient capacity to train all licensed drivers in a short period of time is not feasible, cars must do the teaching. The technology to support fuel efficient driving is already available in many cars, or can be added at very low cost (less than $10).

While not directly discussed as a technology, the introduction of 42 volt electrical systems would facilitate introduction of electric water pumps, idle stop technologies, energy efficient alternators and “mild” hybridization. Until generalisation of 42 volt systems, costs will be high due to the need for a dual voltage (14/42V) system, resulting in poor cost benefit ratios for these technologies.

It appears that current 14V systems could be upgraded to provide idle stop systems at lower cost, but running the air conditioner during engine stop would not be possible. In winter conditions, frequent engine stops may result in offsetting fuel economy loss due to the engine operating below normal temperature. Hence, the economic case for idle stop technology remains unclear. It is possible that “full hybrids” of the Toyota Prius type may be a better, but higher cost solution.

It may be possible to utilize voluntary agreements with manufacturers to introduce cost-effective technologies in specific locations. For example, home air conditioners are now required to meet a certain minimum efficiency level in the U.S., and a similar agreement could be reached for vehicle air conditioners.

Finally, adaptive cruise control (ACC) is likely to be used for comfort/convenience, but fuel economy benefits over a normal (non-adaptive) cruise control may be minimal. ACC can be used in some situations where mechanical cruise control cannot be used, but ACC does not yet have the capability to adapt to full stop-and-go traffic conditions. Overall costs are likely to remain high due to the need for radar, electronic throttle control and brake-by-wire systems. ACC does not appear to be a suitable candidate for any policy actions from an energy conservation viewpoint.

Note

1. Many estimates have been made of the external, or social, costs of oil use – some embedded in more general studies of the social costs of automobile (e.g. a series of reports by Delucchi, 1991-2003, http://www.its.ucdavis.edu/faculty/delucchi.htm). A wide range of estimates exists, for example as reported by Murphy and Delucchi, 1996 and Wahl, 1996[28, 29]. Focusing just on those factors directly related to oil use (and excluding other vehicle related costs such as accidents, traffic congestion, etc.) Wahl reports a range of external cost in the literature of 21 to 134 US cents per gallon (about 5.5 to 35 cents per litre).

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