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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.

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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.

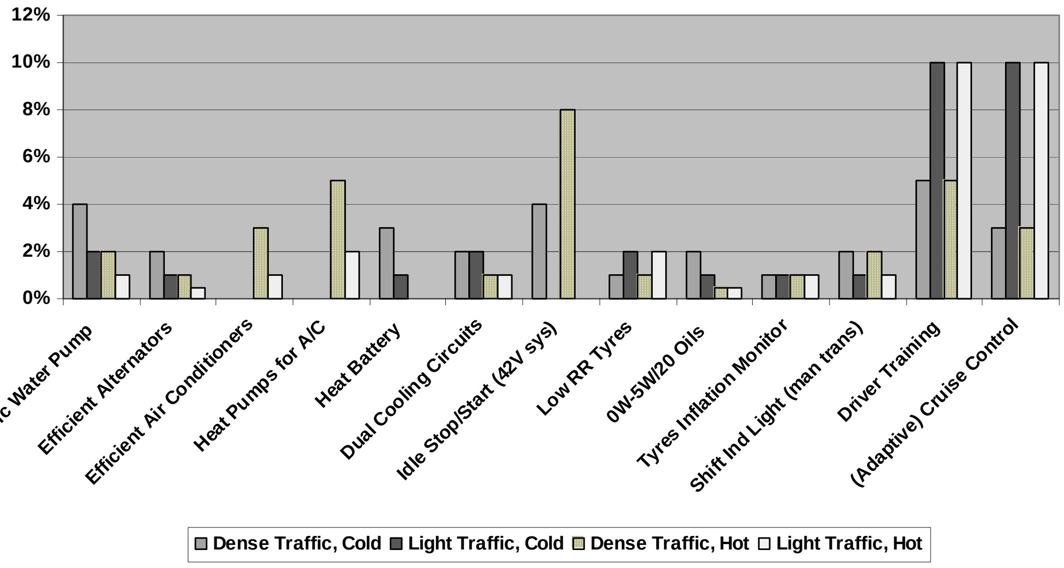
Three cases are considered as examples of the range of these variables encountered among OECD countries. These cases are:

- **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**

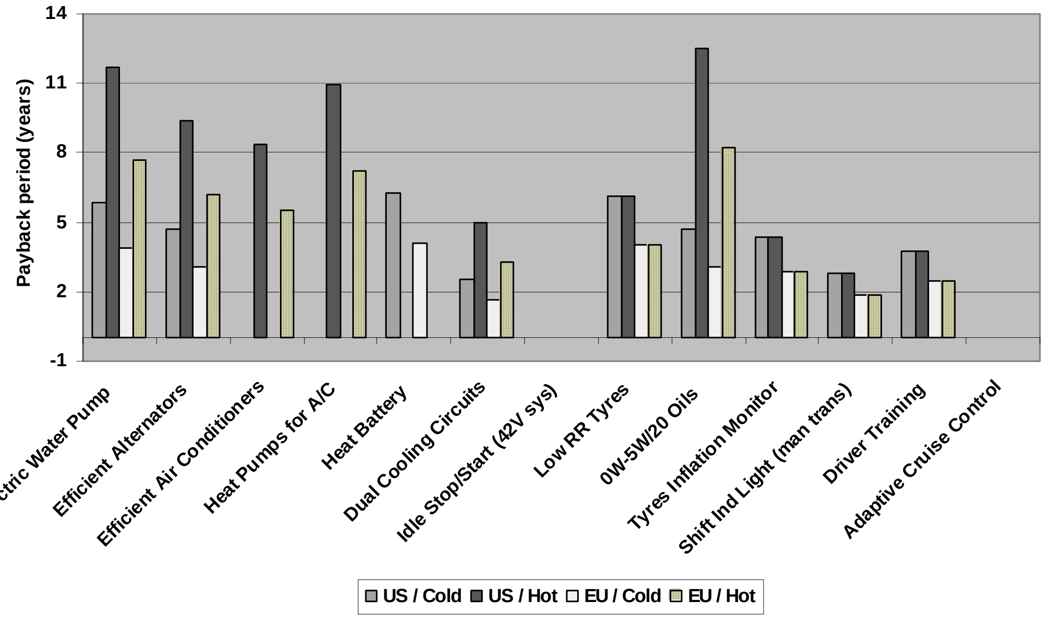


Source: Analysis presented in Chapters 5-7.

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.

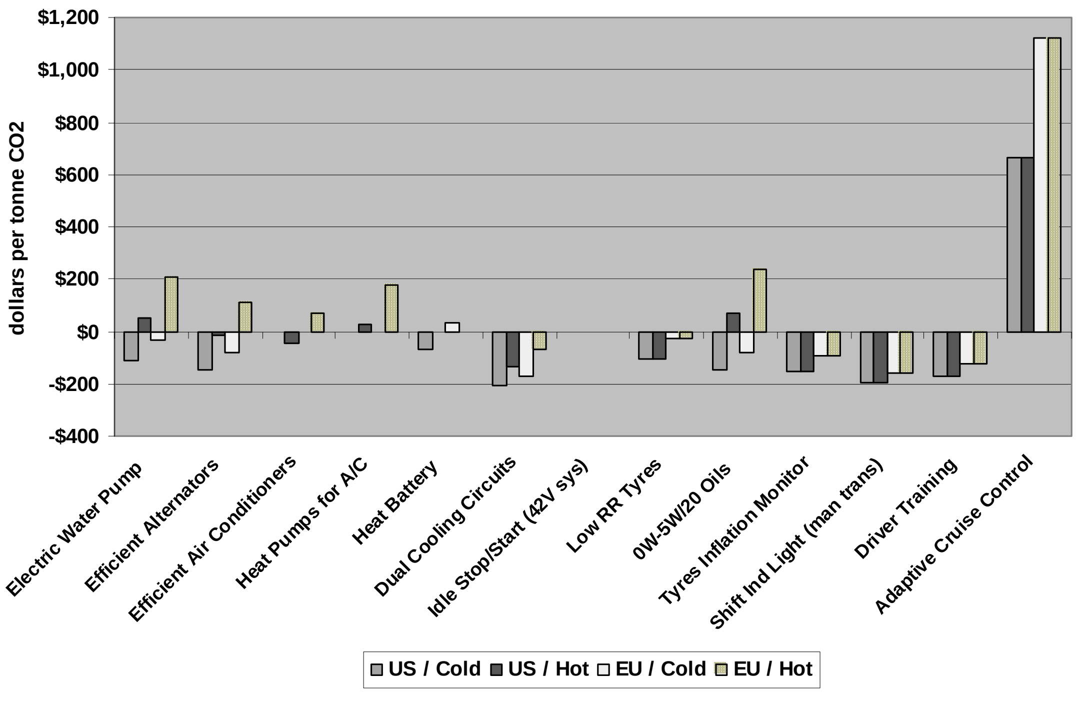
Figure E-2. **Technology Payback Period (Years), Gasoline Vehicles**



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.

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