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Effects of a gear-shift indicator and a fuel economy meter
on fuel consumption

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Summary

This report contains an assessment (mainly based on literature, although some expert knowledge and information from the automotive industry is also used) of the additional vehicle manufacture cost and CO₂ benefits (emission reduction) that can be expected from the introduction of Gear Shift Indicators (GSI) and Fuel Consumption meters (FC meters) for the European Commission, DG Enterprise and Industry for specific contract SI 2.556435, “Expert judgement Benefits Gear Shift Indicator (GSI) and instantaneous feedback fuel meter”, implementing Framework Service Contract ENTR/05/18.

The assessment is done for three different scenarios:

1. GSI without additional feedback system (FC meter).
2. FC meter that provides instantaneous feedback on actual fuel consumption *without* GSI.
3. GSI in combination with a FC meter that provides instantaneous feedback on actual fuel consumption.

A GSI is an in-car system that indicates the optimal gear in case this is different than the currently selected gear, as well as what the driver should do (shift up or down) to reduce fuel consumption. An (instantaneous) FC meter is a display presenting instantaneous fuel consumption, average fuel consumption, fuel consumption when idling or total fuel consumed (see for proposed requirements assumed in this report Annex 1).

GSI

Since no empirical studies have been found in which just a GSI or the combined effects of a GSI and a fuel meter were investigated, an order-of-magnitude estimation was made, based on measured achievable effects, on estimations of the durability of these effects, and on the effectiveness of the system. **It is estimated that a GSI will effectuate a net reduction in CO₂ emission of up to 1.5%.** The likely cost of adding a GSI to a vehicle can be summarized as follows:

	GSI Short term*	GSI Long term
Fleet penetration	currently <5%	mandatory
Costs/vehicle	0-15 Euro	0-7 Euro component costs

*depending on dash board properties and existence of fuel meter, redesign and component costs

Fuel Consumption meter

Based on the literature, short term-effects of a fuel consumption meter are typically a CO₂ / fuel consumption reduction between 1.5% and 5%. Since a fuel consumption meter only provides feedback without any advice, system knowledge and motivation are probably even more important than with a GSI system. Moreover, since it is impossible to objectively define achievable effects, as it is the case for GSI systems, the effects measured in the cited studies are most probably close to actual effects, provided that drivers are motivated to drive fuel-efficiently.

Using similar correction factors as for the GSI effectiveness (30% to incorporate that not all drivers will use the information) and durability (75% to account for a reduction of the effects in the long run), an **overall effect in the order of magnitude of 0.3 to 1.1 %** would remain. The likely cost of adding a fuel consumption meter to a vehicle can be summarized as follows:

	FC meter Short term *	FC meter Long term
Small car fleet penetration	currently <5%	mandatory
Costs/vehicle	Up to 20 Euro	0-10 Euro
Medium car fleet penetration	Unknown	Mandatory
Costs/vehicle	5-10 Euro	0-10 Euro
Large car fleet penetration	currently >95	mandatory
Costs/vehicle	0-10 Euro	0-10 Euro

* depending on dash board properties, redesign and component costs

Synergies of combining a GSI and a fuel consumption meter

When used together a GSI and a FC meter share properties which might affect some of the same driving aspects with an impact on FC, like shifting to the highest gear as possible and shifting up at low engine revolutions. An FC meter however still complements information with a possible positive effect on FC, which is the instantaneous FC at high speeds. This information might lead to the drivers' awareness that lower speeds clearly lead to a lower FC. In general when feed back is given, skills are taught faster and better (Brown, 1989; Seligman, 1978) and could improve the durability to certain extend, (Bangert-Drowns, Kulik, Kulik & Morgan, 1991). Regarding the GSI, an FC meter provides such feedback.

For a combination of both systems it is likely that the advice of a GSI is followed better and / or more often when feedback from a fuel consumption meter is available. **A conservative estimate is that for both systems combined the long term effect is around 2 to 3 % for the average driver. For individual, motivated drivers the effect can be substantially higher.** So, by combining the two instruments, the total effect of the two measures when applied in combination (2-3%) will be larger than their added separate effects (1,8-2,6%) through a larger effectiveness and durability of the GSI and FCM.

Impact on emissions

The implementation of a GSI could increase NOx emissions from diesel cars and some direct injection petrol cars. The introduction of a FC meter could reduce the NOx emission from these vehicles. The magnitude of the total effect when both instruments are implemented is unknown. Further research is recommended to assess the magnitude of the effect as well as its impact on local air quality.

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1 Introduction

Fossil fuel resources are finite and combustion products are widely recognised as contributors to global warming. Road transport is a major consumer of fossil fuels. For these reasons the EU commission has defined strategies to reduce fuel consumption by passenger cars. In order to achieve the defined EU objective of 120 g CO₂/km, measures are evaluated focusing on mandatory reduction of the emissions of CO₂ to reach the objective of 130 g CO₂/km by means of improvements in vehicle motor technology. A further reduction of 10 g CO₂/km has to be established by an increase in the share of bio fuels or other technical improvements such as low rolling resistance tires, efficient mobile air conditioners and in-car devices which support eco-driving.

The European Commission is investigating several regulatory options, amongst which the mandatory introduction of Gear Shift Indicators (GSI) and Fuel Consumption meters (FC meters). A GSI is an in-car system that indicates the optimal gear in case this is different than the currently selected gear, as well as what the driver should do (shift up or down) to achieve lowest fuel consumption. An (instantaneous) FC meter is a display presenting instantaneous fuel consumption, average fuel consumption, fuel consumption when idling or total fuels consumed (but see for proposed requirements assumed in this report Annex 1).

The goal of this study is to investigate the possible benefits and costs of the FC meter and the GSI and of the combined usage of both. The study was performed for the European Commission, DG Enterprise and Industry for contract SI 2.556435, implementing Framework Service Contract ENTR/05/18.

Fuel consumption can be significantly reduced by adopting a fuel efficient driving style. In general, changing driving behaviour can result in a reduction of 15% in fuel consumption. A study by Waters and Laker (1980) into the effect of driving style on fuel consumption, showed a difference of 50% in fuel consumption between the most and the least economical driver. A similar result was reported in a field study by Wilbers (1994): a difference of about 45% in fuel efficiency between the highest and the lowest fuel consumptions (within cars of one brand and type) was measured. Adopting a different driving style is thus a promising tool to reduce fuel consumption. Elements related to gear shifting, speed choice, acceleration and deceleration have the greatest impact on fuel consumption. Fuel efficient driving implies for example: quickly shifting up gears, avoiding high speeds and anticipating traffic conditions in order to avoid unnecessary breaking. Drivers may save between 5% and 25% fuel directly after having received instructions or lessons, depending on their original driving style (Smokers, Vermeulen, van Mieghem, Gense, Skinner, Fergusson, Mackay, ten Brink, Fontaras, & Samaras, 2006).

Technical in-car tools, such as a GSI and fuel meter may be helpful tools to support adopting a fuel efficient driving style. Based on existing literature and expert knowledge and experience, this report provides an overview of the possible benefits and expected usage rates of these systems, either alone or in combination, by passenger cars in real driving conditions.

In Chapter 2, general mechanisms involved in behavioural changes in driving are considered.

Chapter 3 provides an overview of existing knowledge on feasible and long-term effects of GSI and FC meter use. In Chapter 4 additional vehicle manufacturing cost associated with the installation of a GSI / FC meter are assessed. Chapter 5 contains a discussion of conclusions and recommendations.

Three configurations will be evaluated:

1. Driving with a GSI without additional feedback system (FC meter).
2. Driving with GSI in combination with a fuel meter that provides instantaneous feedback on actual FC meter.
3. Driving with a FC meter that provides instantaneous feedback on actual fuel consumption without GSI.

2 Influencing and changing behaviours in driving

Many factors influence the extent to which drivers display fuel efficient driving behaviour. First of all drivers have to **know** about the possible ways to reduce fuel consumption in car driving. Secondly, they need to be **motivated** and willing to display fuel efficient driving behaviour. And finally they should be **able** to adopt the relevant behaviours (Steg, 2008). In order to evaluate, interpret and predict effects of in-car systems on driving behaviour (fuel consumption), it is important to gain insight into these possible levels at which driving behaviour can be influenced. In order to influence driving behaviour different methods can be used (Van der Voort, 2001).

- Information and education on ways to drive fuel efficiently could be provided to the driver.
- Feedback on the effects of specific driving behaviours can be given to the driver.
- In-car systems can be installed which overrule the driver in case driving behaviour is not optimal in terms of fuel consumption.

Since the GSI and FC meter pertain to the first two levels, only these two options will be further discussed here.

Information and education on ways to drive fuel efficiently

Whereas in general people are well aware of the need to reduce energy consumption, a lack of interest and specific knowledge with regard to fuel consumption, emissions and driving is observed. Possible ways to improve knowledge and attitudes towards fuel efficient driving can be by public campaigns and making eco-driving an obligatory part in driver lessons. By these means consumer consciousness can be raised and knowledge on the effects of specific behaviours can be increased. Being informed does not guarantee a behavioural change, but it encourages people to weigh the options before choosing a course of action (Griffioen-Young & Essens, 2004). In-car support, such as a GSI, is by itself not very useful in teaching drivers a new driving style, since it provides no background knowledge or insights, which is essential to establish stable and long-term learning-effects. Nevertheless, such systems can assist drivers in the execution and maintenance of a fuel efficient driving style.

The effectiveness of systems supporting fuel efficient driving is determined by knowledge and motivation. Habitual behaviour is strong. Therefore, the effects of a GSI without having extra information on eco-driving probably remains at a minimum, since drivers are not sufficiently aware of the (financial and environmental) advantages and consequences of their driving behaviour. Providing drivers with information on eco driving via public campaigns or making this an obligatory element during driver education will most probably increase the effects of a GSI. In this case a GSI can be used as a supportive tool in the application of knowledge already present. In the Netherlands about 85% of the car drivers are familiar with the phenomenon of eco-driving. 66% of these drivers reported to be susceptible to eco-driving and to apply one or more eco-driving principles (van Dijk, de Gier, Mulder, van Oosterom, & Wittenberg, 2008). On the other hand, a field study conducted by TNO revealed that people who reported to drive eco-friendly did not apply eco-driving principles better than people who reported not to drive according to these principles (De Goede & Hoedemaeker, 2009).

This suggests that while a considerable share of drivers is motivated to drive eco-friendly and think that they drive accordingly, they are probably not very proficient in applying eco-driving.

Whilst Dutch statistics do not necessarily represent other EU countries, this provides a strong indication that a system, such as a GSI, can be very effective to train the gear shifting technique of eco-driving.

Feedback on the effects of specific driving behaviours

It is a widely acknowledged fact that if learners are provided with immediate information of the consequences of their actions, new skills are learned better and faster (e.g., Brown, 1989; Seligman, 1978). Providing the driver with feedback (for example on fuel consumption) can be useful for motivation, to correct behaviour and to improve performance (Van der Voort, 2001). An advantage of providing feedback in the car is that the driver can observe the direct relation between his/her actions and fuel consumption. In the context of fuel-efficient driving, such feedback can increase the awareness of fuel consumption. Moreover, feedback can provide an indication of driver performance and success of different strategies applied by the driver. This way a driver can discover the optimal strategy.

3 Achievable and actual effects of Gear Shift Indicators and Fuel Consumption meters

The goal of this chapter is to review the potential benefits, in terms of fuel efficiency, of a GSI and FC meter. It is however impossible to consider this issue in isolation from other aspects that define driving style or influence fuel efficiency. When evaluating studied and substantiated effects of systems supporting fuel efficient driving, it is important to make a distinction between achievable effects and actual effects.

Achievable effects refer to the obtainable effects in fuel reduction in case the system's advice is optimally followed. Following the approach of Smokers et al. (2006), actual effects are defined as follows:

$$\text{Actual effect (\%)} = \text{achievable effect (\%)} \times \text{effectiveness (\%)} \times \text{durability (\%)}$$

In which the achievable effect is the reduction that can be obtained by an average driver under average traffic conditions in an average car, effectiveness is the percentage of the exposed people really adapting their driving style and durability is the longevity of the effect (i.e. how much of the effect is maintained in the longer term).

Hereafter, a number of factors that will eventually define the obtained effect will be shortly discussed.

The driver

First of all the driving style drivers had before starting to use the system is of importance, since this determines how much improvement can be achieved. Aggressive drivers have much more potential to reduce their fuel use compared to drivers who are already driving to some extent in a fuel efficient way. In this respect it is also important to consider regional differences in Europe. In southern countries drivers often have a more dynamic, and thus less fuel-efficient, way of driving than people in the northern countries (Smokers et al., 2006). It is therefore assumed that in southern countries a larger fuel consumption reduction can be achieved than in northern countries. On the other hand, the base driving style may affect the willingness to adopt a more fuel efficient style. Whereas aggressive drivers have a large potential to improve their driving style, a fuel efficient style will probably be less appealing to them. People who are already conscious drivers have less to gain, but are probably more willing to further improve. Willingness and motivation are important factors in defining the extent to which people will change their driving style and how robust this effect will be over time. It is also possible that drivers are willing to reduce environmental impact and/or fuel costs, but they do not have the knowledge on how to drive in a fuel efficient way. To increase knowledge as well as to improve attitudes towards fuel efficient driving, information campaigns as well theoretical and practical lessons during driver training courses can be effective.

Driving conditions

Traffic and weather conditions can have a great impact on the extent to which a driver is able to apply a fuel efficient driving style. In addition, the ambient conditions (especially the ambient temperature) have a direct effect on fuel economy (Ang, Fwa, & Poh, 1991). Road conditions (surface quality, gradients) also have their effects (ECMT/IEA, 2005).

Car and Equipment

Besides the driver and the driving conditions, also car characteristics may affect the extent to which a fuel efficient driving style is applied. This was illustrated by results from a field study (Wilbers, 1994): differences of about 30% in fuel efficiency were found between highest and the lowest average fuel consumption of car types.

Presence of noise and vibrations at low engine speeds may prevent a driver from shifting up early. Modern cars, however, are often very well optimized with respect to these matters. Moreover, in-car supporting devices such as a GSI and a FC meter may counteract an intuitive fuel inefficient driving style in older cars.

Also car power may affect driving style. Cars with low powered engines require deep throttle positions to keep up with traffic, which in general could result in a more fuel efficient driving style if it is combined with early upshifts. Cars with high powered engines can more easily keep up with the other traffic and may be in general operated with lower throttle positions. On the other hand, cars with more power can more easily be driven at low engine speeds and may invite these drivers to do so better than drivers of cars with less power would.

Differences can also arise due to differences in driving characteristics between petrol and diesel engines that are generally turbocharged. At low engine speeds, turbocharged diesel engines have relatively high torque, which could encourage the driver to shift up faster (better in terms of fuel efficiency) than with petrol cars. Because diesel engines generally reach their optimal efficiency at lower engine speeds, a maximum engine speed of 2000 rpm for up-shifting is recommended whereas this is 2500 rpm for petrol cars. Recently, in the Netherlands the advised maximum shifting speed of 2000 rpm for diesel engines has been increased and levelled with the advised maximum shifting speed of petrol cars. The reason is that diesel cars show an increase of the NO_x emission when the engine is operated at low speeds and deep throttle positions. Therefore, increasing the advised upshift engine speed from 2000 to 2500 rpm should reduce the increased NO_x emissions.

Finally, the specific characteristics of the employed in-car system, supporting fuel efficient driving, may affect the obtained effects. An analogue FC meter may be more intuitive than a digital one, whereas a digital meter can contain more detailed information. In this report we base our conclusions and recommendations on common variants of a GSI and FC meter (for proposed requirements assumed in this report see annex 1).

Long-term effects (durability)

Positive effects fuel efficient driving support systems on the short run (e.g.: in a short running experiment, until a few weeks after an eco-driving course or directly after buying a new car) may decrease over time. Most studies on advanced driver assistance systems (ADAS) concern measurements over a short period of time. However, since a driver's learning process and behavioural adjustment in reaction to a new ADAS occurs over time, these short term data may insufficiently add to our understanding of driver interaction with the system over time. For example, a study by Lai, Hjämdahl, Chorlton, and Wiklund (2010) showed that drivers who drove with an Intelligent Speed Adaptation (ISA) system overrode the ISA system more often, the longer they drove with it. This effect over time depended however on the road environment and driver characteristics.

Longer-term effects of an eco-driving course were investigated by Beusen et al. (2009). They found that the average fuel consumption four months after the course had decreased by 5.8%. Most drivers showed an immediate improvement in fuel consumption that was stable over time, but some tended to fall back into their original driving habits.

It is known that over time motivation to comply with a system's advice may decrease, or people become annoyed with a system and ignore it or turn it off, for example in case of intervening systems (such as speed control) or annoying sounds or flashes (Lai, Hjämdahl, Chorlton, & Wiklund, 2010). Since both a GSI and a FC meter are systems that are not at all intrusive or distracting, these effects are not expected to occur, or at most to a very moderate extent.

Another issue that has to be taken into account when estimating effects of in-car systems is *behavioural adaptation*. This refers to effects by the system that are non-intended by the introducer of system. For example, some studies suggest that the safety benefits of antilock brake systems (ABS) may be partially offset through behavioural adaptation in the form of driving faster or following closer (Sagberg, Fosser, & Saetermo, 1997). It has been shown that intervening systems (such as Adaptive Cruise Control) might induce an increased feeling of safety in drivers which causes them to drive faster than they used to do without the system (Saad, 2006).

3.1 Effects of a Gear Shift Indicator

A GSI provides the driver with advice on the preferred gear in terms of fuel consumption. A GSI can support and continue the learning process of a fuel efficient driving style for educated drivers, which may help to establish effects of education long-lasting and robust. A GSI may also support uneducated drivers (Smokers et al., 2006). It is however questionable whether drivers without any knowledge on (the effects of) fuel efficient driving are willing to act on a system's advice. Moreover, if drivers do not possess any background knowledge, motivation to act on the system may fade away over time. These considerations stress the fact that it is important to make a distinction between achievable and actual effects.

One study investigated achievable effects of a GSI by comparing regulatory (European Driving Cycle also referred to as NEDC, MVEG-B) and a representative driving cycle for European driving (the regulated European Driving Cycle and the Common Artemis Driving Cycle (CADC)) with the same cycles containing optimal gear shifting points. When comparing the effects of adapted shifting over the European Driving Cycle, a decrease in fuel consumption was obtained of 3% -5%. Over the CADC effects of adapted shifting were a reduction of 7%-11% for petrol and 4%-6% for diesel.

But how should these achievable effects be translated into actual effects in real life? First, it should be noted that no empirical studies have been found in which the effects of only a GSI or of a GSI with a FC meter were investigated. Therefore, an estimate will be made. In order to estimate the effects of a support system, the proportion of drivers who will actually follow the system's instructions has to be incorporated, i.e. *the effectiveness* as well as the *durability*, indicating the the robustness of the system's effects on CO₂ emissions over time.

The advice provided by a GSI will probably be experienced as more relevant and helpful by drivers who possess relevant knowledge than by drivers who are ignorant. Moreover, pre-existing knowledge may increase the durability of effects, since this way the link between knowledge and practice can be strengthened. Non-motivated and/or ignorant drivers might simply ignore the system or even perform the opposite behaviour of what the system advises them to do. Some drivers also may 'test' the system, to see whether it responds correctly to a mistake made on purpose. As argued in the introduction, since the indication of the optimal gear is usually simply indicated by a digit and an arrow in the dashboard, without any auditory feedback or distracting visuals, annoyance will most probably not be an important negative factor in evaluating the long long-term effects of a GSI. Knowledge on the other hand is assumed to have a relatively large influence on the effect of a GSI.

Considering the fact that a GSI supports a learning process, the dissociation between the system's advice and the actual behaviour probably decreases over time. This may set off, at least partly, the negative consequences of decreased motivation over time

Smokers et al. (2006) have estimated that 30% of the drivers will actually follow the instructions of a GSI. According to a study by Wilbers and Wisman (2005) durability of effects on fuel consumption of in-car devices (such as FC meter, econometer, cruise control etc.) is 75%. Combining these values Smokers et al. (2006) (see formula on page 9) concluded that the actual effect on fuel consumption by the application of GSI will be -1.5%.

Van der Voort (2001) investigated the effects of a comprehensive fuel-efficiency support tool ("FEST") that advises the driver on various aspects of driving behaviour: gear shift behaviour, acceleration behaviour, idling, anticipation, etc. The gear shift advice consisted of texts like "Shift earlier from 3->4" presented on a visual display. Such advice was only given when the actual gear choice had deviated from the optimal gear choice for more than a certain threshold. This is in contrast with a GSI which always presents advice as soon as the actual gear deviates from the optimal gear choice. In a field trial with this system, drivers reduced fuel consumption with an average of 11%. For the urban sections a reduction of 20% was even obtained. These effects were measured over a period of 2.5 days. Since the FEST system gave more comprehensive advice than merely gear shift information, it is not possible to extract how much of the improvement was due to the GSI component. However, an analysis in terms of how much advice was given during each run, broken down by advice type, did show that most advices that were generated were related to gear changing (during acceleration as well as during cruising). Furthermore, the results indicated that gear shifting during acceleration improved when driving the FEST system. Taking into account a (probably too conservative) effectiveness (30%) and durability (75%), an actual effect of -2.5 % on CO₂ emission by the FEST system is estimated. Considering the fact that this system also provided advice on acceleration behaviour, the effect of the optimal gear shift advice will be close to the effect that was proposed by Smokers et al. (2006).

Since eco-driving is in general nowadays a familiar topic across the EU, it is estimated that a GSI will effectuate a CO₂ emission reduction of 1.5%. This estimate is based on an effectiveness rate of 30% and a durability of 75% (Smokers et al., 2006).

3.2 Effects of a Fuel Consumption meter

The FC meter gives an instantaneous reading of fuel consumption. Therefore, the driver directly sees the effect of his driving operations upon fuel economy and can use this information to adjust operations to improve fuel economy. In terms of the driving task levels of navigation, manoeuvre and control, the instantaneous fuel consumption is a signal on the control level. It provides a measure of the *result* of the process, without advising the driver how to modify his/her behaviour in order to optimise the process. It varies over driving manoeuvres how easy it is to use this signal in optimising fuel efficiency.

- When driving at a stationary speed, the FC meter is informative with respect to two parameters.
 - Gear selection: when changing to another gear (but still maintaining the same speed), the change in fuel consumption can be read directly from the FC meter.
 - Driving speed: changing the driving speed by e.g. 10 km/h, the changes in fuel consumption can be read directly from the FC meter.
- During acceleration manoeuvres (accelerating from a given initial speed to a given final speed), the fuel consumption is higher than during driving at a more or less constant speed. Using trial-and-error (when trying to optimise e.g. throttle use and gear shift points during the manoeuvre) would require the driver to integrate the instantaneous fuel consumption over the entire manoeuvre. Drivers cannot be expected to perform well on such a task.

Evans (1979) refers to a study by Banowetz and Bintz (1977), who compared fuel efficiency of 70 cars with a miles-per-gallon (mpg) meter to 70 control cars without such a system. All participants were motivated to save fuel. The results showed that the meter-equipped vehicles had about 3% lower fuel consumption than non-equipped vehicles, although the authors reported that this difference was not statistically significant¹.

In the same area, Huntley and Leavitt (1976) conducted a field study in which the fuel economy was compared between a mpg instrumented group and a control group (each containing 73 vehicles, monitored during 6 weeks). All participants were informed about the purpose of the study and were given a booklet on tips for increasing driving economy. The mean fuel consumption was 1.5% lower for the instrumented group, but this difference was not statistically significant¹.

In a study by Af Wählberg (2007), the long-term effects of a training programme on fuel efficient driving were investigated. This was done for bus drivers in a city environment. After twelve months of training the mean overall effect obtained was a reduction of about two percent fuel consumption. In the same study, a FC meter was added as well. This system gave a further reduction of fuel consumption of about two or three percent. Again, these were long long-term effects (comparing six months before with six month after installation of the device in the analysis).

The field study of Van der Voort (Van der Voort, 2001) also contained an experimental group with a fuel meter (Eco-log).

¹ The uncertainty was larger than the observed difference which means that the result is likely to have occurred by chance.

A control group that had no system but the instruction to drive as fuel-efficiently as possible, without increasing travel time had a fuel consumption reduction of 3.4%. An additional reduction of 3% was obtained with the help of the Eco-log system, although this increase was not significant¹.

Econometer

Much like a FC meter, the econometer gives visual feedback about instantaneous fuel efficiency. The measurement principle (and thus the information presented) is different, i.e. measuring inlet manifold pressure rather than actual fuel consumption. Still, because of the similarity in the type of output, findings regarding econometers are also presented here.

Evans (1979) discussed two studies where participants drove a fixed route through an urban environment. Various driving instructions were applied, including "drive normally with the traffic", "minimize fuel consumption", "maintain fuel economy meter in the green region", and "maintain fuel economy meter in the green or orange region". Effects of the various instructions were compared against the "driver normally" instructions in terms of fuel consumption and driving behaviour. Results showed that the fuel reduction under the "minimize fuel consumption" (10%) was larger than under the econometer conditions (5% for orange and green). This difference was attributed to better anticipation in the "minimise fuel consumption", e.g. to skilfully adjust the speed to avoid stops at traffic signals. A rapid acceleration as such is fuel consuming, but having to brake, wait (with the engine running at idle) and accelerate typically uses more fuel.

Wilbers and Salverda (1993) mentioned that there was hardly any literature on econometers. They described a field study by Larsen (1991), who found no significant effect of the econometer on fuel efficiency. Wilbers conducted a field study on econometers (1994), where it was reported that econometers improved fuel efficiency. There were two groups of participants:

- private drivers: they had to pay for their own fuel costs *and* had to register their fuel consumption during the trials;
- business drivers: they did not have to pay for their own fuel costs *and* did not have to register their fuel consumption (because this was done via the tank card company).

Results showed that the econometer improved fuel efficiency, especially for the private drivers. Business drivers had higher fuel consumption to start with, and they had much smaller improvements due to the econometer. These effects are illustrated in Figure 1.

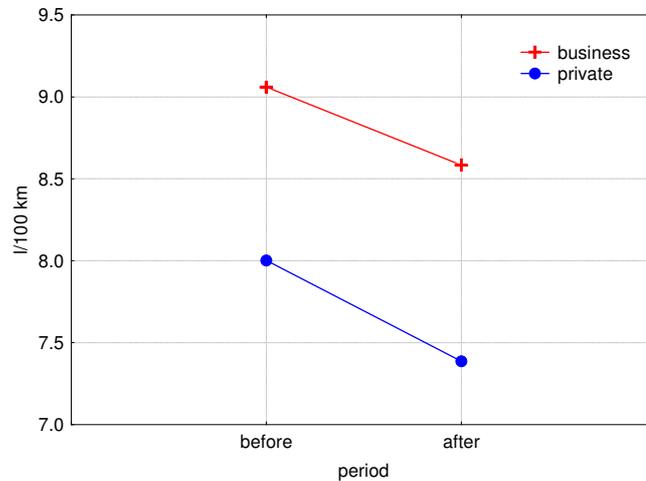


Figure 1; Effects of econometer on fuel efficiency (derived from Wilbers, 1994, Table 1).

The gross savings were 8.1% for the private drivers and 4.4% for the business drivers. The study of Wilbers (1994) also included control groups, where participants did not have an econometer but where fuel consumption was registered in the same way as in the econometer group. In the control groups, fuel consumption was reduced as well in the after period with respect to the before period: 6.6% for the private drivers and 5.3% for the business drivers. This illustrates that just raising a driver's awareness of fuel-efficiency can reduce fuel consumption.

3.3 Combined effect of a Gear Shift Indicator and a Fuel Consumption meter

No empirical studies have been found in which the combined effects of a GSI and a FC meter were investigated. A GSI and a FC meter can affect driving behaviour at different levels. A GSI provides advice whereas a FC meter gives feedback. Kroon, M. (2008) suggests that no large change in driving behaviour will occur without any in-car feedback about actual fuel use.

In this paragraph an estimate of the possible combined effects will be made based on the individual effects and on the way they possibly interact when the systems are combined. A GSI in principle has no influence during other driving situations than on shifting during acceleration and cruising, whereas a FC meter can additionally affect driving situations/behaviour like e.g. coasting and cruising at high speeds. From this we can conclude that a GSI and a FC meter are not fully complementary.

In the table below an overview is given of studies that investigated the effect of fuel meters on fuel consumption and the GSI.

Table 1; Overview of studies that investigated the effect of fuel meters and GSI on fuel consumption.

Reference	FC reduction	Conditions	Remarks
Fuel Consumption meters or indicators			
Banowetz Bintz (1976)	3%	70 cars and equal size control group	FC meter Result was not statistically significant*
Huntley and Leavitt (1977)	1,5%	73 cars and equal size control group	FC meter; Result was not statistically significant*
Af Wählberg (2007)	2 to 3%	Busses Long term (6 months)	FC meter Reduction in addition to reduction due to eco driving training
Van der Voort (2001)	3%		Eco-log
Evans (1979)	5%		Achievable effect of the Economometer
Larsen (1991)	No significant effect		Economometer
Wilbers (1994)	4,4	Business drivers private drivers	Economometer
	8%		
GSI			
Vermeulen (2006) and Smokerset al. (2006)	6% 1,5%	Mix of petrol and diesel cars	GSI, achievable effect (100% follow up) Achieved effect assuming 30% effectiveness and 75% durability

* with 'statistically not significant' it is meant that the difference that was observed between two situations was smaller than the uncertainty. The observed difference was therefore likely to have occurred by chance.

Since no data or studies are available on the combined effectiveness of the GSI and the FCM the following sections describe the *possible* ways a FCM and a GSI can affect FC both in a positive or a negative sense. After such an evaluation, an overview is obtained of all possible effects, taking into account the fact that some effects might be complementary, some might overlap or some might counter-balance.

Finally, an attempt to quantify the combined effects of a FCM and a GSI is made based on the assumed increased effectiveness and durability rates.

Gear selection during acceleration

Depending on driver and interpretation the FC meter can have a positive or negative effect during accelerations; a sportive driver may be stimulated by seeing the very high values and try to lower them by shifting at lower engine revolutions. A moderate driver may perceive the high instantaneous values at deeper gas pedal positions as negative, which may prevent him from using the deep throttle position and higher engine efficiency and instead use less throttle at lower engine efficiency. A GSI may pursue a driver to still try the shifting at lower engine speeds. But also the momentarily high values of the FCM at low engine speed combined with a deep throttle position may be interpreted as an indication that the GSI gives a wrong advice.

For drivers with eco driving experience this possible adverse effect will probably not occur as they were trained to drive that way. How effects will balance out for gear selection during acceleration given the distribution of driver types is not known.

Gear selection for cruising

For cruising a FC meter very probably confirms the advice of the GSI, namely shifting up to the highest gear where the engine runs smoothly. Cruising at a higher gear has a clear positive effect on fuel economy which can be easily observed at the instantaneous FC meter if the throttle pedal is kept steady and if the road is flat. *In general, it can be stated that learning supported by (positive) feed back improves the learning process and to a certain extend also the long term durability of it* (Bangert-Drowns, Kulik, Kulik & Morgan, 1991). Such feedback is provided by the FC meter since it functions as a constant reminder of a driver's (positive) behaviour. Optimal gear selection for cruising has a large effect on FC because much of the VMT (vehicle miles travelled) are performed cruising. At higher speeds gear selection has no impact because it is assumed that most drivers would have chosen the highest gear anyway. Increasing speed then has negative impact on FC which can be seen on the FC meter but can not be influenced by shifting any more. This is where a FC meter has an impact of its own.

When gear shifting alone is considered the gear selection for cruising probably has the highest effect on FC and adds to the positive effects of gear selection at lower speeds during acceleration. This together will outweigh possible negative effects of a small group who might interpret GSI advice during accelerations as wrong.

Some unique effects of each system are believed to sustain and add to the combined effect when both systems are used together. A unique functionality from the FC meter is indicating a high FC at high speeds which might invite drivers to drive slower. Another unique functionality from the FC meter is to show instantaneous fuel cut-off during coasting which also may lead to a positive effect on FC.

Summarizing, it can be stated that there is a range of functionalities of a GSI and a FC that *could* inform the driver in such a way that adaptation of the driving style or certain properties of the driving style change in such a way that FC is affected. There are functionalities that overlap because they affect the same behavioural property, there are unique functionalities that sustain when combining systems and there are functionalities or mechanisms that might amplify or weaken the effects of each unique system when combined.

The functionalities of both systems which might affect fuel consumption and which overlap for both systems;

- During accelerations: information from the FC meter about high instantaneous FC when shifting up at high engine speeds which might lead to shifting up at lower engine speeds. This is consistent with the advice from the GSI to shift up at low engine speeds.
- During cruising: information from the FC meter about instantaneous FC, and the fact that generally at a higher gear the FC is lower, might lead to a more economical gear choice. This is consistent with the advice of the GSI to shift to the highest, most economical gear.

A functionality of the FC meter which might affect FC and which is complementary after combination;

- Information about a higher instantaneous FC at higher speeds when shifting is no issue anymore. This might lead to lower average speeds and hence, to a lower FC.

A functionality that might amplify, add or strengthen the effect after combination;

- Information about trip integrated fuel consumption but also about instantaneous fuel consumption which confirms the correct application of the GSI (advice with positive feedback). In chapter 2 it is discussed when feedback is given, skills are generally taught faster and better (Brown, 1989; Seligman, 1978) and even might improve the durability to a certain extent (Bangert-Drowns, Kulik, Kulik & Morgan, 1991). This might thus increase the effectiveness and durability of both systems. Although such mechanisms are widely known and acknowledged, for this given situation actual effects have never been investigated and thus can only be estimated to be positive. I.e. *the combination of a GSI and a FC meter probably leads to a further improvement and possibly also to a more durable change of driving behaviour* with respect to fuel consumption, provided that a driver is motivated.

Functionalities that might weaken or decrease the combined effect after combination;

- So far no functionalities or mechanisms are known which might weaken the combined effect. Some studies referred to a rebound effect (Gottron, 2001) (Greening, Greene, and Difiglio 2000), Beusen et al (2009), but the reported effects were either small or not present. Real-world field studies of the combined usage of the GSI and FC meter have never been performed, however. A possible effect sometimes referred to in discussions around a GSI is that the system might be experienced as annoying or patronizing to the driver and therefore be deliberately avoided. This might probably only lead to a zero effect for those drivers.

In how far all these functionalities and effects add to each other to a final combined effect for the different types of drivers is not known from literature because these were never actually investigated. Nevertheless, both systems have shared and complementary functionality with a potential to reduce FC which sustains and could improve effectiveness and durability of both when combined.

In order to estimate the combined effect of a FCM and a GSI, a calculation has been made based on the achievable effects of a FCM, a GSI and the effectiveness and durability rates² quoted in chapter 3 (30% and 75% respectively). Table 2 shows an overview of this data.

² The achievable effect is the reduction that can be obtained by an average driver under average traffic conditions in an average car, effectiveness is the percentage of the exposed people really adapting their driving style and durability is the longevity of the effect (i.e. how much of the effect is maintained in the longer term).

Table 2 Summarized effects of a GSI and FCM used as input to calculate an estimate of the combined effects

	GSI	FCM
<i>Achievable effect (lower estimate) [%]</i>	7	1,5
<i>Achievable effect (higher estimate) [%]</i>	N/A	5
<i>Effectiveness rate [%]</i>	30	30
<i>Durability rate [%]</i>	75	75
<i>Achieved effect (lower estimate) [%]</i> ³	1,5	0,3
<i>Achieved effect higher estimate) [%]</i>	N/A	1,1

If we add the achieved effects of both measures, the combined effect would be between 1,8% (for the lower estimates) and 2,6% (taking into account the higher estimate for the FCM). Based on the arguments above, an expert guess was made that the product of the effectiveness and durability rates increases by some 10% to 15% due to the synergies between a GSI and a FCM. Using this 10% to 15% increase in effectiveness and durability, this leads to the following assumed combined achieved effects

Achieved combined effect (lower estimate) = 1,8 * 1,10 = 2%

Achieved combined effect (higher estimate) = 2,6 * 1,15 = 3%

It is therefore conservatively estimated that the combined effect is around 2-3% for the average driver but for individual, motivated drivers may lead to significantly higher reductions.

3.4 Effects of the GSI and the FC meter on noxious emissions

A secondary effect of applying a GSI was observed; A study, in which an emission test program was performed to assess a range of measures to decrease fuel consumption of modern passenger cars (Vermeulen, 2006), showed that besides effects of a GSI on CO₂ and fuel consumption under some conditions effects on other, noxious emissions can be expected as well.

For following the advice of a GSI in comparison with regular shifting modern diesel passenger cars show an increase of the NOx emission of 15-30% over both the legislative test cycle as well as over a driving cycle which is more representative for real world driving, the CADC urban and rural parts. For two petrol cars with a direct injection engine an increase of the NOx emission was observed as well. The increase of the NOx emission of these cars was not found statistically significant. Most likely this is due to the small sample. For conventional petrol cars with port fuel injection an increase of CO and HC emissions and a small decrease of the NOx emissions was observed. The emission levels of HC these cars are very low however and the increases found are small in an absolute sense as well. For CO the levels and the increase were higher and on average exceeded the type approval limit values. CO however is not of major concern as a local pollutant.

³ The achieved effect is equal to the achievable effect multiplied by the effectiveness and durability rates. See chapter 3 for more information.

The effects of an FC meter on noxious emissions have never been investigated. It is expected that an FC meter does not result in an increase of any emission component, however. Rather, it is expected that an FC meter has a beneficial effect (decrease) on emissions if the FC meter would lead to lower average speeds on the motorway, more fluent driving, better anticipation and more coasting. The effect of a lower speed and more fluent driving on a motorway is demonstrated in the same investigation. NO_x emissions of diesel cars decrease 25% when traffic flow is steady compared to 'traffic forced driving' where traffic flow is more dynamic. The NO_x emissions of diesel cars decrease another 20% if the speed drops from 100 to 80 km/h. In this study only a limited set of motorway cycles was measured; the study focused on the effect of strict speed control and speed limitation on a Dutch motorway. Effects of speed reductions from other motorway driving situations have not been investigated.

For the combined use of a GSI with a FC meter the effects on global noxious emissions might improve compared to a GSI alone situation, although real effects are not known. Furthermore, taking the overall efficiency of the application of a GSI of 25% (durability x effectiveness), which might be increased by the combined usage of a FC meter, the expected effect on real world NO_x emission will not be at the level as was measured in the lab as the results of these tests can be regarded as achievable and not as achieved effects. Due to a certain effectiveness of the GSI (not all people will follow the shifting advice) the achieved real world increase of NO_x would be lower than was measured.

For NO_x however, not only the effect on total emissions is important, the local emissions are important as well. For current diesel cars and possibly also for DI petrol cars, the NO_x emissions increase due to shifting up at lower engine speeds. These emissions contribute to local pollutant concentrations on the street level which in many EU cities at the moment is still problematic when NO₂ is concerned. It is not known how much a certain increase of NO_x emissions of passenger cars due to adapted shifting would contribute to local air quality. It seems worthwhile to calculate possible effects by means of an emission model to see the actual contribution to local pollutant concentrations.

While the earlier mentioned emission testing program clearly showed an increased NO_x emission for current passenger cars, for future passenger cars as of Euro VI (which has more stringent limits for NO_x and other pollutants) the effects on real world NO_x emissions are not known.

If the GSI would become part of a legislative procedure, for instance to measure the possible benefit on CO₂ emissions, and one would need to minimize the risk on elevated NO_x emissions in the real world, some regulatory measures could be considered.

Examples are;

- Including measurements using the GSI in the EU TA type I test to test both regulated noxious emissions and Fuel Consumption and CO₂ emissions at the same time/test, with the requirement that when using a GSI the regulated emissions would remain within the limits and
- Controlling off-cycle emissions and including the GSI as a possible normal driving condition

Each option does not exclude the need for the other.

4 Vehicle modification, functionality and cost estimate

4.1 Functionality

Gear Shift Indicator

Under normal driving conditions a GSI recommends the gear to be selected in order to obtain the lowest fuel consumption. This advice is given on a display presenting both the suggested gear as well as an indication of what the driver should do to get to that gear (i.e. shift up or down). It is assumed that exact requirements will be developed for the definition of fuel efficient shifting at a later stage, but a preliminary set of requirements is included in annex 1.

Fuel consumption meter

A FC meter is a device that shows the actual fuel consumption of the vehicle in l/100km, the integrated fuel consumption over a user-selectable trip and the fuel consumption over the life time of the vehicle. The instantaneous or trip information is visible at all time. Exact requirements will have to be developed at a later stage, but a first proposal is included in Annex 1.

4.2 Hardware and software

Gear Shift Indicator

The hardware of a GSI consists of a panel or area in the vehicle's dash board able to display e.g. a digital number indicating the preferred gear. This panel also contains an area where e.g. arrows can be displayed to show the advice of the direction of a shifting action (up or down).

For control of the panel additional wiring is required. Generally, information regarding the shift advice can be communicated through the vehicles CAN interface. Computing the advised gear can generally be done in the vehicles ECU where already much (if not all) of the required information is available and is being processed to calculate parameters required for computation of a gear shift advice. Known algorithms for e.g. automated gear boxes use maps of throttle pedal position, being an indication of power demand from the driver and actual engine and vehicle speed. The existing software thus only needs to be extended with a map for gear shifting advice, added with correction formulae for situations where load and speed differ significantly from regular driving (trailer towing, mountains, etc.).

Instantaneous Fuel Consumption meter

The hardware of a FC meter consists of a panel or area in the vehicle's dash board or console providing the possibility to display a digital number indicating the actual fuel consumption. Furthermore, it may consist of an operation button to cycle through other information like for instance average trip fuel consumption, kilometers to refueling etc.

For control of the panel additional wiring is required. Generally, information regarding the fuel consumption can be communicated through the vehicle's CAN interface. Computing the fuel consumption can generally be done in the vehicle's ECU where already much (if not all) of the required information is available and is being processed to calculate parameters required for computation of the amount of fuel to be injected.

4.3 Costs

Gear Shift Indicator

Currently, most vehicles do not have a special area or location reserved for a GSI on the dashboard. This would mean that implementation of a GSI on the short term would require additional effort to redesign the dash board panel and to adapt the production process. The redesign most probably will only consist of adding an armature in the panel where the GSI can be fixed. Some current designs might need more intrusive adaptation as the existing panels do not have enough room for the GSI.

For existing dashboard designs with a lead time to market of about 3 years there are additional costs for redesign and adaptation of the production process. For dashboard designs being developed after introduction of legislation on GSI in the EU it is assumed that the additional effort is very low.

The questionnaire on MAC (Mobile Air Conditioners) and GSI delivered some statements from stakeholders regarding additional costs of a GSI; a GSI would cost less than 7 Euro per vehicle in case only few modifications need to be done and up to 15 Euro per vehicle if additional modifications need to be done to the dashboard/instrument panel. Another respondent mentions that for vehicles with an on board FC meter there are no additional costs whereas there are for vehicles without on board FC meter. The exact magnitude of these extra costs are however unknown. From this, the likely cost of adding a GSI to a vehicle can be summarized as follows:

	GSI Short term*	GSI Long term
Fleet penetration	currently <5%	mandatory
Costs/vehicle	0-15 Euro	0-7 Euro component costs

*depending on dash board properties and existence of fuel meter, redesign and component costs

Instantaneous Fuel Consumption meter

Currently, onboard computers with instantaneous FC consumption meters are more and more seen on passenger cars. For large passenger cars the on board computer is often part of the standard package. For middle class cars the on board computer is often optional or part of a special package. In case an onboard computer is present in small cars it is often only available as part of the most exclusive package. Some brands which offer so-called fuel efficient models include an instantaneous FC meter standard in the package or in an ‘eco’ package.

For most current passenger cars the instantaneous FC meter is part of the on board computer, which is more or less a display which provides user selectable information to the driver. In such systems actual or instantaneous fuel consumption is often available. If available, the instantaneous fuel consumption can be selected by cycling through a set of the display options. An instantaneous FC meter may also be a separate display unit located in the vehicles dashboard or be part of a more simple/small on board computer display located at the dashboard.

Currently, most small vehicles do not have a special area or location reserved for an instantaneous FC meter.

This would mean that implementation of such a meter on the short term would require additional effort to redesign the dash board panel and to adapt the production process. The redesign most probably will only consist of the addition of an armature in the panel where the display can be fixed. Some current designs might need more intrusive adaptation as the existing panels do not have enough room for the display. For existing dashboard designs of small cars with a lead time to market of about 3 years there are additional costs for redesign and adaptation of the production process. For dashboard designs being developed after mandatory introduction in the EU it is assumed that the additional effort is very low.

For most of the medium cars the space or location for addition of an on board computer display is yet available since it is already reserved for the models where it is an option or part of a package. In that case no redesign or adaptation of the dashboard is required and additional costs mainly consist of component costs.

For calculating the cost benefit of FC meters it is important to take into account the fact that currently a certain share of the vehicles is already equipped with such devices. Users of cars with FC meters probably have a reduced potential of further improving fuel economy. In their case addition of a GSI may still cause an additional improvement.

For the definition of the costs of an on board fuel consumption meter the costs of a GSI can be used as a basis. A FC meter is namely based on the same working principles and requires more or less the same hardware, with the exception of the addition of a small control button to cycle through the fuel meters display options. Other aspects determining costs are as explained above the existence of this type of hardware on current vehicles and the possible need to adapt dashboard designs if fuel meters would become mandatory. As most small vehicles do not have the option for a FC meter nowadays for such vehicles the short term costs are expected to be somewhat higher. The costs decrease towards larger cars as there FC meters are common good and costs only represent component costs and assembly costs.

From this, the likely cost of adding a FC meter to a vehicle can be summarized as follows:

	FC meter Short term *	FC meter Long term
Small car fleet penetration	currently <5%	Mandatory
Costs/vehicle	Up to 20 Euro	0-10 Euro
Medium car fleet penetration	Unknown	Mandatory
Costs/vehicle	5-10 Euro	0-10 Euro
Large car fleet penetration	currently >95	mandatory
Costs/vehicle	0-10 Euro	0-10 Euro

* depending on dash board properties, redesign and component costs

For calculating cost benefit of a GSI and working out legislative requirements it is important to consider the risk of a possible impact on tail pipe emissions. For diesel vehicles with current technology shifting up at lower engine speeds in urban driving causes NO_x emissions to increase.

Future legislation should therefore either aim at least at a zero effect on NO_x emissions or take into account the societal costs of the increased NO_x emissions in urban areas.

5 Discussion and conclusions

The effects of systems supporting fuel efficient driving are dependent on attitudes motivation (attitudes), knowledge and ability. Apart from driver characteristics, driving conditions and vehicle properties, these factors are to an important extent affected by information campaigns and driver training and education. Notwithstanding the fact that eco-driving is in general nowadays a familiar topic across the EU, Dutch research indicates that despite a widespread motivation to drive eco-friendly, drivers do not always apply the rules properly (De Goede & Hoedemaeker, 2009). This provides a strong indication that tools to support fuel efficient driving can be effective.

Few studies have empirically addressed the effects of systems supporting fuel efficient driving. To the author's knowledge no empirical study specifically addressed the effects of a GSI on CO₂ emission or the obtainable effects as tested under laboratory conditions. Concerning FC meters, mainly short term effects have been investigated. Therefore, estimations with regard to effects of GSI systems should be considered as an order of magnitude, whereas the effects of FC meters are more substantiated. Despite the fact that empirical data in general are scarce, together with expert knowledge and experience these findings provide an indication of the extent to which these systems can contribute to a fuel efficient driving style. Nevertheless, in order to evaluate and employ these estimations properly, it is important to take into account some important issues. One such issue concerns the applied research method. To assess the effects of a GSI or a FC meter in an empirical study, control conditions are needed. A comparison can be made with a control group (i.e. drivers who do not have such a device), a before-after comparison, or - preferably - both. Even such an ideal design has the problem that participants in the control conditions usually are (have to be) informed of the nature of the study. This information can raise their awareness on the fuel efficiency of driving, which can trigger changes in their driving behaviour that already improves fuel efficiency. After all, various studies have shown that when asked to drive more fuel efficiently, participants are typically able to do so (Evans, 1979; Van der Voort, 2001). Indeed, in several studies indications were found that the control conditions were influenced as well (Beusen, Broekx, Denys, Beckx, Degraeuwe, Gijsbers, Scheepers, Govaerts, Torfs, & Panis, 2009; Wilbers, 1994; Af Wählberg, 2007). Such effects result in an underestimation of the improvements due to a GSI or FC meter.

Behavioural adaptation

Besides methodological issues, possible adverse effects on the long term also have to be taken into account. Behavioural adaptation refers to effects by the system that are non-intended by the introducer of system. Behavioural adaptation due to annoyance by the systems under consideration are not expected (or at most to a moderate extent). For GSIs and FC meters, a so-called 'rebound effect' could occur. More economical driving yields lower costs per km driven. When the fuel costs per litre remain constant, this could yield an increase of the travelled kilometres, offsetting the impact of the efficiency gain. This effect is known as the rebound (or 'take-back') effect (Gottron, 2001). For increasing automobile fuel economy, an overview of Greening, Greene, and Difiglio (2000) showed that this rebound is generally reported to be in a low range (between 10% and 30% of the economical benefit is spent on increasing mileage).

It should be noted that their overview only contains (econometric) studies conducted in the USA. Beusen et al (2009), in their study on eco-driving in Belgium, found that fuel consumption reduced after the training course, but they found no significant effect on distance travelled (i.e. no indications of a rebound effect).

Gear Shift Indicator

Since no empirical studies have been found in which just a GSI or the combined effects of a GSI and a FC meter were investigated, an order-of-magnitude estimation was made, based measured achievable effects, on estimations of the durability of these effects, and on the effectiveness of the system. Based on earlier studies and taking into account the fact that eco-driving is in general a familiar topic across the EU, it is estimated that a GSI will effectuate a net reduction in CO₂ emission of up to 1.5%. This estimate is based on an obtainable effect of 6%, an effectiveness rate of 30% and a durability of 75% (Smokers et al., 2006).

Fuel Consumption meter

Based on the literature, short term-effects on fuel consumption of a FC meter are typically between 1.5% and 5%. Since a FC meter only provides feedback without any advice, system knowledge and motivation are probably even more important than with a GSI system. Moreover, since it is impossible to objectively define achievable effects, as it is the case for GSI systems, the effects measured in the cited studies are most probably close to actual effects, in case drivers are motivated. Using correction similar factors as for the GSI effectiveness (30% to incorporate that not all drivers will use the information) and durability (75% to account for a reduction of the effects in the long run), an overall effect in the order of magnitude of 0.3 to 1.1 % would remain.

GSI and Fuel Consumption meter

In how far all functionalities of a GSI and FC meter add to each other to an overall combined effect is not known because this was never actually investigated. Nevertheless, both systems combined have shared functionality with a potential to reduce FC for 1,5% at the minimum and additionally have a complementary functionality which sustains and even functionality which might improve effectiveness and durability of the other. Combining the advice of a GSI with the feedback of a FC meter is assumed to strengthen the effects by each unique system. It is therefore conservatively estimated that the combined effect is more than 1,5 % at around 2-3 % for the average driver but for individual, motivated drivers may lead to significantly higher reductions.

6 References

- Af Wählberg, A.E. (2007). Long-term effects of training in economical driving: Fuel consumption, accidents, driver acceleration behavior and technical feedback. *International Journal of Industrial Ergonomics*, 37 (4), 333-343.
- Ang, B.W., Fwa, T.F., & Poh, C.K. (1991). A statistical study on automobile fuel consumption. *Energy*, 16 (8), 1067-1077.
- Bangert-Drowns R.L.; Kulik, C.C.; Kulik, J.A.; Morgan, M.T.(1991). The instructional effects of feedback in test-like events. *Review of educational research*. 61: 213-238.
- Banowitz, R. A. & Bintz, L.J. (1977). *Field evaluation of miles-per-gallon meters* (Report No. DOT-TSC-OST-77-64). Washington, D.C.: U.S. Department of Transportation.
- Beusen, B., Broekx, S., Denys, T., Beckx, C., Degraeuwe, B., Gijssbers, M. et al. (2009). Using on-board logging devices to study the longer-term impact of an eco-driving course. *Transportation Research Part D: Transport and Environment*, 14 (7), 514-520.
- Brown, I.D. (1989). *How can we train safe driving?* Traffic Research Centre.
- De Goede, M. & Hoedemaeker, M. (2009). *Daadwerkelijk Rijgedrag met Het Nieuwe Rijden* (TNO-DV 2009 C284). Soesterberg, the Netherlands: TNO Defence, Security and Safety - Human Factors.
- ECMT/IEA (2005). *Making Cars More Fuel Efficient: Technology and Policies for Real Improvements on the Road* (report). Paris, France: OECD/ECMT and IEA.
- Evans, L. (1979). Driver behaviour effects on fuel consumption in urban driving. *Human Factors*, 21 (4), 389-398.
- Gotttron, F. (2001). *Energy Efficiency and the Rebound Effect: Does Increasing Efficiency Decrease Demand?*
- Greening, L.A., Greene, D.L., & Difiglio, C. (2000). Energy efficiency and consumption - the rebound effect - a survey. *Energy Policy*, 28 (6-7), 389-401.
- Griffioen-Young, H.J. & Essens, P.J.M.D. (2004). *How to influence and change behaviours in a traffic context* (TM-04-D019). Soesterberg, The Netherlands: TNO.
- Huntley, M.S. & Leavitt, W.Z. (1976). *The effectiveness of miles-per-gallon meters as a means to conserve gasoline in automobiles* (Report No. DOT-TSC-OST-76-38). Washington, D.C., USA: Department of Transportation.
- Kroon, M. (2008) Contribution of Martin Kroon to Public consultation on gear shift indicators, available at:
http://ec.europa.eu/enterprise/sectors/automotive/files/environment/mac/consultation/martin_kroon_en.pdf
- Lai, F., Hjämdahl, M., Chorlton, K., & Wiklund, M. (2010). The long-term effect of intelligent speed adaptation on driver behaviour. *Applied Ergonomics*, 41 (2), 179-186.
- Larsen, G. B. (1991). *Muligheder for brændstofbesparelse i personbiler og mindre varebiler*.
- Saad, F. (2006). Some critical issues when studying behavioural adaptations to new driver support systems. *Cognition, Technology and Work*, 8 (3), 175-181.
- Sagberg, F., Fosser, S., & Saetermo, I.A.F. (1997). An investigation of behavioural adaptation to airbags and antilock brakes among taxi drivers. *Accident analysis and prevention*, 29 (3), 293-302.

- Seligman, C. (1978). Feedback as an energy conservation strategy. *Proceedings of the Human Factors Society – 22nd annual meeting*, (pp. 539-540).
- Smokers, R., Vermeulen, R., van Mieghem, R., Gense, R., Skinner, I., Fergusson, M. et al. (2006). *Review and analysis of the reduction potential and costs of technological and other measures to reduce CO2-emissions from passenger cars* (SI2.408212). Delft, The Netherlands: TNO Science and Industry.
- Steg, L. (2008). Promoting household energy conservation. *Energy policy*, 36 4449-4453.
- Van der Voort, M.C. (2001). *Design and evaluation of a new fuel-efficiency support tool* (PhD thesis). Enschede, The Netherlands: University of Twente, Faculty of Technology & Management.
- van Dijk, T., de Gier, M., Mulder, S., van Oosterom, J., & Wittenberg, W. (2008). *Onderzoek toepassing Het Nieuwe Rijden*. (F2608). Amsterdam, the Netherlands: TNS NIPO.
- Vermeulen R., (2006). *The effects of a range of measures to reduce the tail pipe emissions and/or the fuel consumption of modern passenger cars on petrol and diesel*, TNO report IS-RPT-033-DTS-2006-01695, December 22, 2006
- Waters, M.H.L. & Laker, I. B. (1980). *Research on fuel conservation for cars* (921). Crownthorne, England: Transport and Road Research Laboratory.
- Wilbers, P. & Wisman, L. (2005). *Beïnvloeding rijgedrag: Too soft to handle? Monitoring en evaluatie Het Nieuwe Rijden* Goudappel Coffeng.
- Wilbers, P.T. (1994). *De econometer - een praktijkproef - Fase 2* (Rapport TT94-69). Veenendaal: Traffic Test.
- Wilbers, P. T. & Salverda, J.C. (1993). *De econometer - een orienterend onderzoek naar de mogelijkheden om met visuele feedback zuinig rijden te bevorderen. Fase I* (Rapport TT93-7). Veenendaal: Traffic Test.

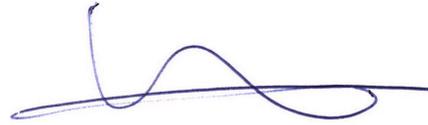
7 Signature

Delft, 17 December 2010

A handwritten signature in blue ink, consisting of a large, stylized 'B' followed by a horizontal line and a smaller signature.

B. Bos
Head of Department

TNO Science and Industry

A handwritten signature in blue ink, featuring a large, stylized 'S' followed by a horizontal line and a smaller signature.

S. Bleuanus
Author

Annex 1: specification proposal for GSI and Fuel Consumption meter

This annex contains a first proposal for a set of requirements for on-board computers/fuel economy meters. This proposal is not meant to be exhaustive. It is based on the “in car minimum requirements” document initially authored by Mr. Martin Kroon who kindly offered to share it with the consultants.

Instantaneous fuel consumption meter (FC meter)

Display

The on-board computer/FC meter must be equipped with a display presenting fuel consumption data in analogue or digital form. It is probable that, due to the fact that the instantaneous fuel consumption needs to be displayed as l/100km as well as l/hour (when idling, see further on), that a digital representation is preferred.

Data presentation

The on-board computer/FC meter must provide at least the following data:

1. Instantaneous fuel consumption: l/100 km;
2. Average fuel consumption: l/100 km;
3. Fuel consumption when idling: l/hour;
4. Total fuel consumed (over the lifetime of the vehicle).

Ad 1: Instantaneous fuel consumption must be presented immediately after the vehicle starts moving. “Moving” is defined as vehicle speed above 10km/h.

Ad 2: Average fuel consumption must comprise the fuel used over the distance covered since the last ‘reset’ action.

Ad 3: Fuel consumption while idling must always be presented when the engine is idling. Idling is defined as: vehicle stationary with engine running.

Ad 4; Total amount of fuel consumed over the lifetime of the vehicle in litres.

The data presentation aforementioned may only be temporarily overruled by other sorts of data to be displayed in case of:

- (Road) safety emergencies;
- Risk of running out of fuel;
- Technical failures.

Choices that can be made by the driver. The fuel meter will show:

a) Average fuel consumption since the last reset action (data presentation 1)

OR

b) Instantaneous fuel consumption when driving OR when idling (data presentation 2 or 3)

OR

c) Total fuel consumed (lifetime vehicle), when this is selected, the fuel meter should automatically revert after 10 seconds back to a) or b)

It shall not be possible for the driver to turn the display off entirely.

Location of the display

The display for the on-board computer/FC meter must be positioned at one of the following locations: When an engine revolution counter is present in the vehicle, the display must be located in or immediately next to this engine revolution counter. When no engine revolution counter is present, the display must be located in or immediately next to the speedometer.

The location chosen for the display shall always be above knee level of an average driver's length. The average driver's length shall be derived from the regular driver's size as actually applied by the car manufacturers.

Visualisation of the display

The driver must be able to read the information displayed about instantaneous or average fuel consumption or fuel consumption when idling easily from a regular seating position during all (meteorological) conditions.

- The instantaneous fuel consumption figure presented must vary as frequently as needed to present real values to the driver but not more frequently than every second and not less frequently than every three seconds, whenever the fuel use varies during driving. The fuel consumption figure displayed should be filtered in a way that the fuel meter does not show effects on fuel consumption that cannot be influenced by the driver (i.e. lambda regulation strategies, soot filter regeneration, etc.).

Operating the on-board computer/fuel consumption meter

The driver must be able to operate the on-board computer/fuel consumption meter easily from any regular driver's position. The driver should from this position be able to:

- a) switch the type of data being displayed
- b) reset the average fuel consumption measurement

Reliability of the data displayed

- The fuel consumption data displayed shall not deviate from the real fuel consumption more than 5%.

Gear Shift indicator (GSI)*Display*

The GSI must be equipped with a display presenting both the suggested gear if this is higher or lower than the currently selected gear, as well as an indication of what the driver should do to get select that gear (i.e. shift up or down) to achieve lowest fuel consumption.

Data presentation

The GSI shall provide the data in the following way:

1. Suggested gear: as a numerical indication of the suggested gear (i.e. 1, 2, 3, etc).
2. Shift indication if the currently selected gear is not the suggested gear: as an arrow pointing either up or down to indicate if the driver needs to select a higher or lower gear respectively.
3. If the currently selected gear is equal to the suggested gear, the indications 1 and 2 shall be off completely.

Location of the display

The display for the GSI meter must be positioned at one of the following locations: When an engine revolution counter is present in the vehicle, the display must be located in or immediately next to this engine revolution counter. When no engine revolution counter is present, the display must be located in or immediately next to the speedometer.

The location chosen for the display shall always be above knee level of an average driver's length. The average driver's length shall be derived from the regular driver's size as actually applied by the car manufacturers.

Operating the GSI

The driver shall not be able to switch off or change the behaviour or data representation of the GSI in any way.

General comments:

- Fuel meter and GSI minimum size and appearance shall be such that a driver interested in using the fuel meter can (whilst driving the vehicle) safely and easily read and comprehend the displayed data.
- Both instruments shall comply with ECE R121, "UNIFORM PROVISIONS CONCERNING THE APPROVAL OF VEHICLES WITH REGARD TO THE LOCATION AND IDENTIFICATION OF HAND CONTROLS, TELL-TALES AND INDICATORS"