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Reducing fuel consumption and emissions in urban areas by using a new fuel-efficiency support tool

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Abstract

Road transport still depends almost entirely on liquid fuels derived from natural oil. Combustion of these carbon-based fuels naturally results in the emission of carbon monoxide and dioxide, which play an important role in global warming. Improving fuel-efficiency through a change in driver behaviour can effectively reduce fuel consumption and corresponding emissions. Since fuel consumption is most substantial in urban areas, the largest gain is likely to be obtained here.

A new-generation fuel-efficiency support tool has been designed that aims at reducing fuel consumption by inducing a change in driver behaviour. The support tool includes a normative model that formulates optimal driver behaviour in this respect based on the context the vehicle is in. If actual behaviour deviates from optimal behaviour, the support tool presents advice to the driver on how to change driver behaviour.

Evaluation of the new advice system took place in a driving simulator as well as on the road. The advice system has proven to be particularly effective in the urban environment; an average reduction in fuel consumption of 20 percent was achieved. Mainly an altered gear choice and quicker gear changing caused this reduction. In addition drivers learned to anticipate more to oncoming traffic situations.

Supporting drivers to adapt their driving behaviour therefore results in a significant reduction of fuel consumption and therewith carbon dioxide emission. The willingness to adapt driving behaviour will be consolidated by lower fuel costs on drivers' behalf.

1 Introduction

Road transport still depends almost entirely on liquid fuels derived from natural oil. Large-scale substitution by alternative fuels will not take place in the short to medium term due to institutional barriers (Groenewegen & Potter [1]). Since other sectors in the economy are able to find substitutes, the share of oil used by road transport is likely to increase. The world's resources of oil, however, are rather limited. In addition there is an increasing public awareness about the problems caused by pollution from automobiles. The combustion of fossil fuels leads to the emission of hydrocarbons, carbon monoxide and dioxide, oxides of nitrogen and sulphates. The emission of oxides of nitrogen and sulphur dioxides causes acidification, which causes forests and the flora and fauna in lakes to die. Carbon dioxide is responsible for over half of the man-made greenhouse effect and therefore has been identified as the main greenhouse gas at the present. Although carbon monoxide is not itself a greenhouse gas, it plays a part by removing hydroxyl radicals (-OH) from the atmosphere, which act as a sink for the greenhouse gas methane. The recognition of the negative impacts of road transport has resulted in policy mainly with regard to the reduction of carbon dioxide and differentiation and variability of the costs of travel. Fuel conservation, that is performing the same (or similar) transport task with less fuel consumption, is a sensible strategy to limit the negative impacts of road transport.

The largest potential to improve fuel economy in road transport probably lies in enhancing vehicle technology (Decicco & Ross [2]). However such an approach has a relatively long implementation time. The most effective way to improve fuel economy in the short term is to aim at a change in driver behaviour, which can result in a reduction in fuel consumption of up to 15% (Waters & Laker [3]). An additional benefit of aiming at a change in driver behaviour is that the improvement achieved will still be valid when new vehicle technology becomes available. Together they can reduce fuel consumption even further.

To induce more optimal driver behaviour, the driver must be provided with feedback. In the past several driver support tools have been developed to improve fuel economy directly or indirectly. However, a review of available devices revealed that none of the devices was able to bring about the levels of fuel reduction judged possible, because of some major shortcomings (Van der Voort & Dougherty [4]). It was concluded that for a driver support tool to significantly improve fuel economy, it should:
i) Provide drivers with clear, accurate and non-contradictory information,
ii) Take into account the present context of the vehicle,
iii) Place no requirements on drivers that are too high to safely combine with the actual driving task,
iv) Work within both urban and non-urban environments.
One potential way to meet these requirements is to provide the driver with direct information on *how* to drive more fuel-efficiently.

2 A new-generation fuel-efficiency support tool

Taking into account the previously described system requirements a new-generation fuel-efficiency support tool has been designed. It is a purely advisory system. The driver can decide whether to accept the advice given by the support tool. The prototype of the support tool comprises three basic components: inputs, a data processing module and a human-machine interface.

2.1 Inputs

The inputs to the system can be divided into two categories: measured inputs and system parameters. Preferably, a support tool should use measured inputs that are readily and cheaply available from existing in-vehicle systems and technologies. Therefore only parameters such as vehicle speed, engine speed, clutch, gear position, accelerator position, steering angle, braking force and headway were used as an input to the system.

As well as measured variables, the proposed system requires various parameters to be set. These can be separated into two classes. The first class is vehicle and engine related. They take into account the differences between types of car. Important parameters of this type are the fuel consumption map, engine characteristics, gear ratios, vehicle weight, rolling resistance and air resistance.

The fuel consumption map is the key to the whole system. It is a three-dimensional plot of specific fuel consumption versus engine rotational velocity versus mean effective pressure. Note that specific fuel consumption is defined as the ratio of useful power produced to the rate of fuel consumption. The fuel consumption map is usually represented in two dimensions by plotting equal specific fuel consumption contours on a graph that has the other two variables as axes. The lowest point of this contour map represents optimum fuel consumption and is known as the '*sweet spot*'. One of the basic aims of the advice system is to keep the operating point of the engine as close to the sweet spot as possible, particularly during acceleration.

The second class of parameters is used to tune the behaviour of the system. Typical examples of such parameters are speed limits, minimum 'driveability' acceptable for the average driver, and how long advice should be displayed for.

2.2 Data processing module

The data processing module is based on a concept known as a *normative model*. It describes the optimal driver behaviour for a wide range of contexts known as *states*. Typical states are cruising, idling, decelerating, accelerating, gear changing. State determination is necessary because optimal driver behaviour depends heavily on the context in which the vehicle is being driven. Rules and advice on optimal behaviour should therefore apply to this context.

Actual driver behaviour is compared with the optimal behaviour using the normative model. The structure of the model is multi-layered. The lowest layer is known as the *tactical* level and is concerned only with the immediate past. The next level up is known as the *strategic* level and uses a longer history of recorded measurements to provide a temporal context. A series of identical states is grouped and defined as a *manoeuvre*. The unit of analysis for the tactical model is normally a single manoeuvre. On the tactical level, for each type of manoeuvre, a module of the normative model calculates the optimal behaviour for minimum fuel consumption. The strategic level consists of a set of rules and concentrates on identifying particular predefined sequences of manoeuvres.

If the difference in behaviour is large, non-optimal behaviour is diagnosed. This in turn leads to an advice that is considered for presentation to the driver by means of a suitable human-machine interface. The generated advice consists of a pointed advice on how to change driver behaviour in order to reduce fuel consumption. It is related either to cruising, idling, acceleration, deceleration, gear changing during cruising, gear changing during acceleration or anticipation. To avoid presentation of only negative advice, positive feedback will be provided to the driver if he or she has driven fuel-efficiently for more than 4 minutes.
A *scheduler* determines whether or when the advice is presented. This scheduler includes a safety check verifying whether a particular advice causes a dangerous situation within the current driving context. Axiomatic safety considerations take priority over fuel consumption and therefore advice will be delayed or cancelled in such a case.

2.3 Human-machine interface

The human-machine interface consists of a small TFT-screen that visually presents detailed advice to the driver on how to change driving behaviour. For example, an advice could be "Shift earlier from the 2nd to 3rd gear" (figure 1).

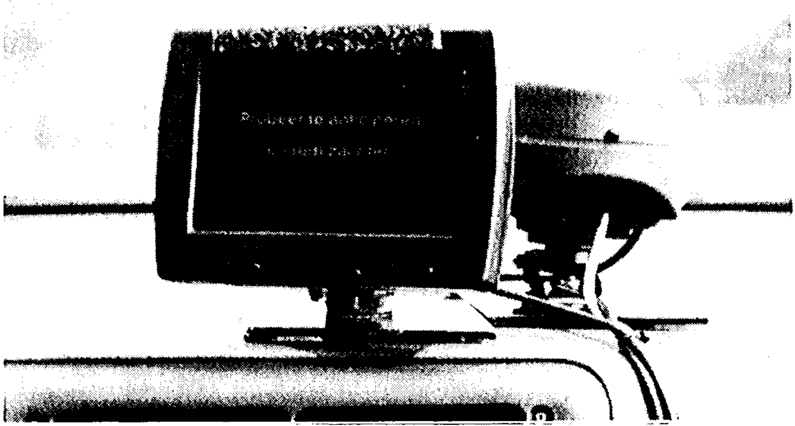

Figure 1: Human-machine interface

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3 Experimental design

The new support tool has been evaluated in a driving simulator experiment as well as in a field experiment. The aim of the driving simulator experiment was a first evaluation of the support tool. A driving simulator provides a controllable and safe environment. In addition, the most effective human-machine interface was selected in this experiment. In the second phase a field experiment was set up to test the fuel-efficiency support tool in an actual traffic situation. Moreover, it was possible to assess the impact of the system over a longer period of time in the latter experiment.

3.1 Driving simulator experiment

The driving simulator experiment is set up according to a between-subject design. In this design participants are exposed to only one condition, and the effect of the conditions is assessed by comparing the performance of participants, who have been exposed to different conditions. In the experiment the new advice system was judged against an existing system (a miles-per-gallon meter) and a control group. Three experimental groups were defined:

i) a control group with no support,
ii) a reference group using the miles-per-gallon meter,
iii) the focus group with the new fuel-efficiency support tool.

Each of the three groups consisted of 20 participants.

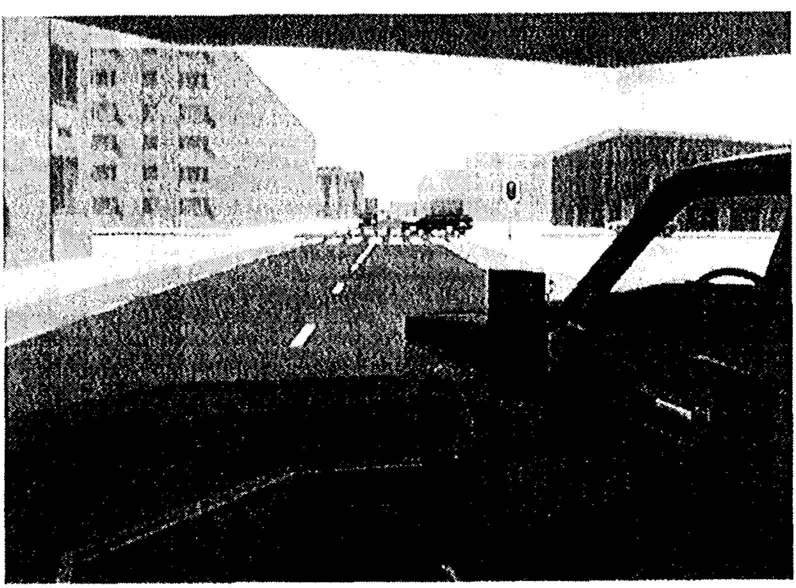

Figure 2: Driving simulator

Each participant drove 6 runs through (virtual) urban, sub-urban and highway environments (figure 2). The first run consisted of normal driving. In the second run the participants were instructed to drive as fuel-efficiently as possible, keeping trip time constant however. During run 3-6 the participants - with exception of the control group - received feedback from the support tool assigned to them.

3.2 Field experiment

Also in the field experiment a between-subject design was chosen, and three experimental groups were defined:

i) a control group without support,

ii) a reference group using an existing state-of-the-art device that is readily available on the car accessories market (the Eco-log system), and

iii) the focus group driving with the new fuel-efficiency support tool.

Each group consisted of 12 participants. Similar to the driving simulator experiment, the conditions were varied over the measurements. To evaluate the fuel-reducing capabilities and the driver characteristics, fuel consumption and driving behaviour with support (except for the control group) were compared with outcomes while driving normally or driving fuel-efficiently without support.

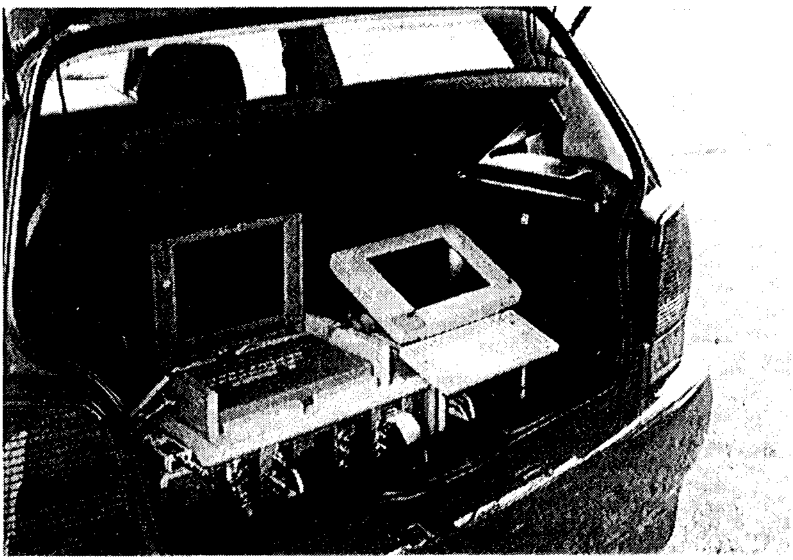

Figure 3: The instrumented vehicle

A measurement within the field experiment consisted of driving a prescribed route through urban, rural and highway environments. The route has a total length

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of 28.5 kilometres and a distribution of urban, rural and highway kilometres of 42%, 26% and 32% respectively. Participants had to drive this route within 45 minutes. In total each participant performed 5 runs that were recorded. To avoid impact of unfamiliarity with the vehicle used in the field experiment (figure 3), participants made at the beginning of the experiment one run that was not recorded. In between the measurements the vehicle was available to the participants for own use. This experimental strategy made it possible to assess the impact of driving with a device over a longer period.

4 Results

To assess differences in fuel-efficiency as accurate as possible, the results with regard to fuel economy (litres per 100 km) were assessed rather than fuel consumption (litres) itself; fuel economy allows for small differences in travelled distance between the participants.

The driving simulator experiment revealed a significant difference in fuel consumption between the focus group and the control and reference groups [Kruskal-Wallis ANOVA; $p<0.05$]. In the urban environment, drivers were, with the assistance of the new fuel-efficiency support tool able to reduce fuel consumption by on average 23% compared with normal driving. Compared with driving fuel-efficiently without support, the new support tool caused an additional reduction of 14%. The reference group was only able to obtain an additional reduction of 5%. Figure 4 shows the development of fuel economy over the runs that are described in Section 3.1.

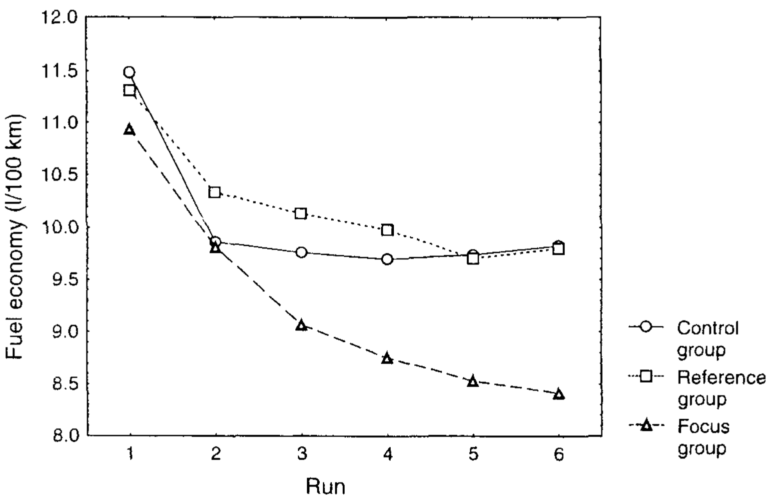

Figure 4: Urban fuel economy –Driving simulator experiment

The driving simulator experiment showed that the fuel reduction was caused largely by a change in driver behaviour with respect to gear changing during acceleration: drivers accelerate at the same pace, but change earlier to a higher gear. In addition an increased level of anticipation was found.

These promising results were corroborated by the field experiment. Although the measured input variables may have been not as precise as simulated input, the advice from the fuel-efficiency support tool still resulted in a significant reduction in fuel consumption. All participants were able to reduce fuel consumption significantly when asked to drive fuel-efficiently; on average participants saved 5.8% fuel in the urban environment. However, with the help of the fuel-efficiency support tool participants were able to reduce fuel consumption by an additional 15.8%. Compared with their normal driving behaviour these participants reduced fuel consumption on average by 20.2%. An additional reduction of only 7.7% was obtained with the help of the existing device, the Eco-log system. The Control group also obtained an additional reduction of 5.6% as a result of practice. The development of fuel economy during the field experiment is shown by figure 5.

The additional reduction caused by the fuel-efficiency support tool was even slightly higher during the field experiment, since in the driving simulator participants already reduced fuel consumption by 10% when asked to drive fuel-efficiently (without support). Also under real traffic circumstances the fuel-efficiency support tool has proven to be able to induce fuel consumption reductions, which are in the range of the levels of fuel reduction judged possible by Waters & Laker [3] as opposed to existing devices.

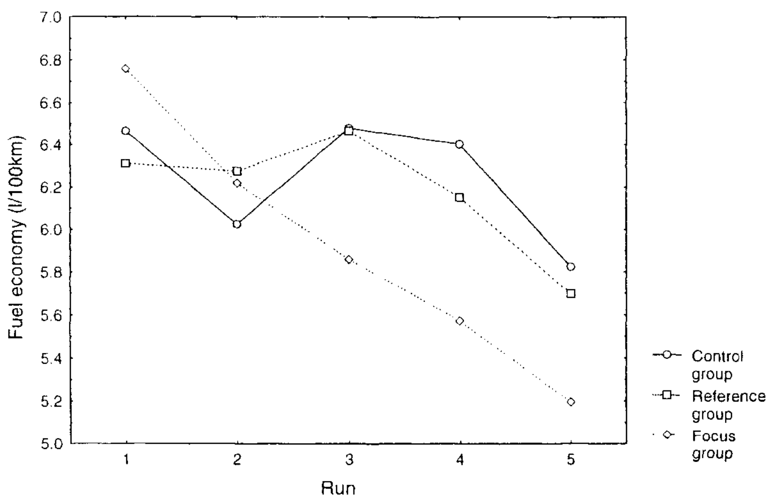

Figure 5: Urban fuel economy – Field experiment

In the field experiment the impact of the fuel-efficiency support tool was assessed over a 2.5-day period. The development of fuel consumption over the runs in this period was not only affected by time and experience but also by traffic volume. With the new support tool participants were able to overcome the impact of higher traffic volumes on fuel consumption, whereas with the existing device participants could only limit the impact compared with no support. The continuous decrease in fuel consumption also indicated that participants kept learning from the new support tool on how to minimise fuel consumption over the 2.5-day period. The fuel reductions could therefore even increase if the support tool would be permanently available to the driver.

Analysis of adaptation made in driving behaviour revealed that during the assistance of the new fuel-efficiency support tool drivers drove significantly more often in 5th gear, turned off the engine more often while idling, anticipated more and drove more smoothly. These findings differ from the driving simulator experiment. One explanation could be that the vehicle in the field experiment had a more powerful engine in respect to its size than the driving simulator. Therefore participants could have assumed that this vehicle was more suited to accelerate in a higher gear. Furthermore this vehicle was equipped with a 5-gear box whereas the driving simulator only had a 4-gear box. This could have made gear choice during cruising more complicated.

5 Conclusions

A new-generation fuel-efficiency support tool has been designed that aims at reducing fuel consumption by inducing a change in driver behaviour. The support tool includes a normative model that formulates optimal driver behaviour based on the context the vehicle is in. If actual behaviour deviates, the support tool presents advice to the driver on how to change driver behaviour.

Evaluation of the new advice system took place in a driving simulator as well as on the road. The advice system has proven to be particularly effective in the urban environment; an average reduction in fuel consumption of 20 percent was achieved. Mainly an altered gear choice and quicker gear changing caused this reduction. In addition drivers learned to anticipate more to oncoming traffic situations. The willingness to adapt driving behaviour will be consolidated by lower fuel costs on drivers' behalf.

As a rule, the emission of carbon dioxide reduces proportionally to the reduction in fuel consumption. The 20% fuel reduction in urban areas caused by the new fuel-efficiency support tool is therefore likely to result in a comparable reduction in CO_2-emissions. The fuel reduction is obtained by a change in driving behaviour that causes the engine to operate at a higher fuel-efficiency. In this case the engine is operated at low engine speeds and high engine torque. Although this is the fuel-efficient part of the engine map, cars are generally not calibrated to operate under these conditions. It has the disadvantage that the fuel-efficient driving behaviour has a negative impact on the emission of CO, HC and NO_x. A study by TNO Automotive has shown that under these engine conditions the emission of CO can triple, and the emission of HC and NO_x can increase with

74% and 35% respectively (Gense [5]). Therefore an adapted calibration for new vehicles is recommended in order to reduce vehicle emissions other than carbon dioxide simultaneously. Furthermore policy should provide guidelines with respect to which emission reductions should get priority.

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