DESIGN AND EVALUTION OF
A NEW-GENERATION FUEL-EFFICIENCY SUPPORT TOOL

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ABSTRACT

An effective way to reduce fuel consumption in the short run is to induce a change in driver behaviour. In this project, a new-generation fuel-efficiency support tool has been designed. The support tool includes a normative model that formulates optimal driver behaviour minimising fuel consumption. If actual behaviour deviates from this optimal behaviour, the support tool presents advice to the driver on how to change driver behaviour. Evaluation of the new support tool by means of a driving simulator experiment revealed that drivers were able to reduce fuel consumption by 16% compared with 'normal driving' and by 7% compared with driving fuel-efficiently without support. Within the urban environment, reductions of up to 23% were found. In addition the new support tool was evaluated with regard to secondary effects.

INTRODUCTION

Energy consumption in its present volume and composition is using up our scarce resources. Furthermore, the pollution resulting from this energy consumption has a negative effect on the environment. Although several new energy-supply technologies are emerging, the world's consumption of fuels derived from natural oil keeps increasing every year. Oil is, however, one of our finite resources. Therefore, fuel conservation, that is performing the same (or similar) transport task with the consumption of less fuel, is a sensible strategy.

The largest potential to improve fuel economy in road transport probably lies in enhancing vehicle technology (1). However such an approach has a relatively long implementation time. The most effective way to reduce fuel economy in the short term is to aim at a change in driver behaviour, which can lead to a reduction in fuel consumption of up to 15% (2). 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. Several driver support tools have been developed in the past 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 (3) concluded that for a driver support tool to significantly improve fuel economy, it should:

- ?? provide the driver with clear, accurate and non-contradictory information
- ?? take into account the present context of the vehicle
- ?? place no requirements on the driver which are too high to safely combine with the actual driving task
- ?? 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.

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 that 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.

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 that different types of car are not identical. Important parameters of this type are the fuel consumption map of engine, 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 which 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' characteristics acceptable to the average driver and how long advice should be displayed for.

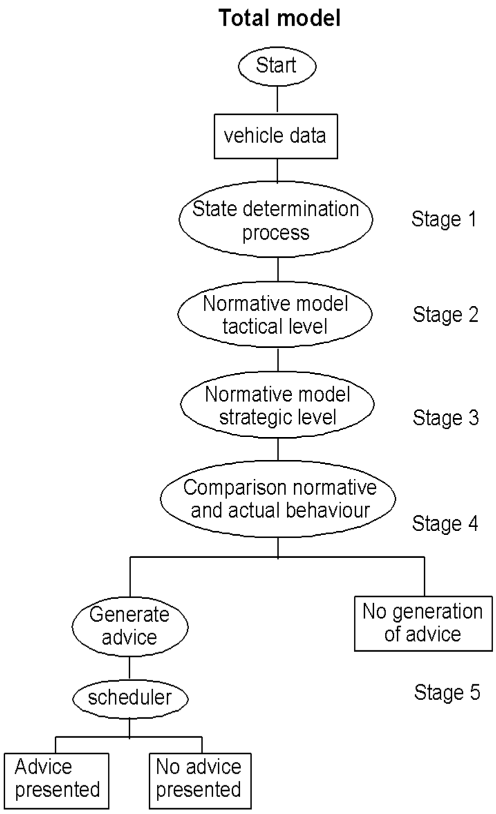

Figure 1 Structure of the data processing module

Data processing module

The data processing module is based on a concept known as a *normative model*. A schematic of the structure of this module is shown in Figure 1. The normative model describes the optimal driver behaviour for a wide range of contexts known as *states*. Typical states that are identified 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 normative 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. The boundary between the immediate past and further back in time (which is dealt with by the strategic model) is defined as the last time a state transition took place. A series of identical states is therefore 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 normative model of optimal behaviour for minimum fuel consumption has been developed. 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 advice being generated which is proposed to be presented to the driver by means of a suitable human-machine interface. The generated advice consists of a direct advice on how to change driver behaviour in order to reduce fuel consumption. The advice is related to either cruising, idling, acceleration, deceleration, gear changing during cruising, gear changing during acceleration or anticipation. In total, 27 different predefined advices can be generated. 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. Whether or when the advice is presented is determined by the scheduler. The scheduler includes a safety check that verifies if a particular piece of advice could not lead to a dangerous situation within the current driving context. Axiomatic safety considerations take priority over fuel consumption and therefore advice will be delayed or cancelled if following it could lead to a dangerous situation. More details of the data processing module can be found in (3).

Human machine interfaces

Two human-machine interfaces (HMIs) have been designed. These are identical, except that they have different ' advice length'. A distinction is made between advice and extended advice. For extended advice, more details are provided to the driver. For instance, if the advice is: “Shift earlier”, the matching extended advice might be: “Shift earlier from 2nd to 3rd gear”. An example of the extended advice interface is shown in Figure 2. One key aspects of the driving simulator experiment, that will be described in the next section, was to determine which of the two HMI is the most effective.

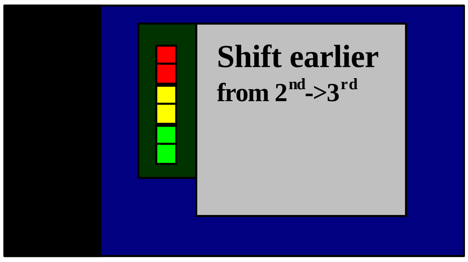

Figure 2 The human machine interface for extended advice

DRIVING SIMULATOR EXPERIMENT

The new fuel-efficiency support tool was evaluated with regard to the ability to reduce fuel consumption through a driving simulator experiment. In the experiment, which was carried out at the TNO Human Factors Research Institute in The Netherlands, the advice system with each of the interfaces was judged against existing systems and a control group. The existing systems were related to the miles-per-gallon meter.

In total, 88 male subjects participated, equally divided over the four groups, that is the Control group, Existing group, Advice group and Extended advice group. Each participant drove 6 runs through urban, sub-urban and highway environments. 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 (e.g. a between-subject comparison).

RESULTS

Comparison of the fuel economy (measured over the total trip in litres/100 km) obtained by the drivers in the four groups revealed no difference between the four groups during the first two runs. It means that the participants in the different groups act equally before the provision of feedback. So, all differences found during runs 3-6 were due solely to the presence of a feedback system.

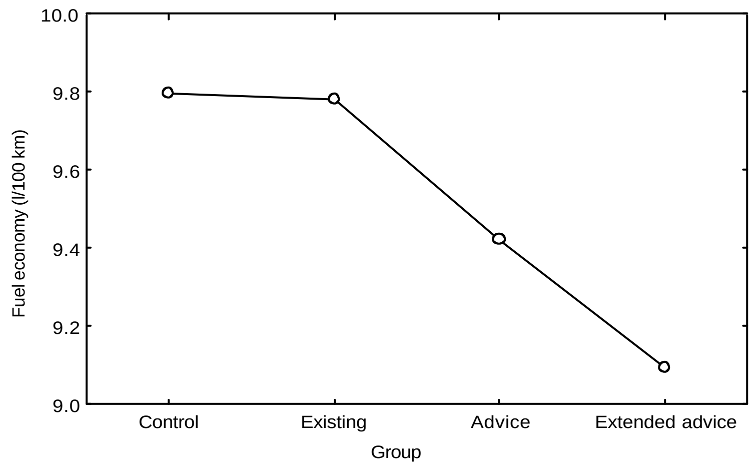

Figure 3 Effect of Group on Fuel Economy (l/100 km) for the total trip

During runs 3-6, significant differences between the groups were found (Kruskal-Wallis ANOVA; $p<0.005$) (See Figure 3). A post-hoc multiple comparison (Tukey HSD) showed that the group supported by the extended advice system drove significantly more fuel-efficiently, both compared with the control group and with the group supported by the existing systems ($p<0.01$). No significant effect of the length of the advice was found. However, only the group presented with extended advice drove significantly more fuel-efficiently than the control group. Therefore, it is inferred that it is best to present the driver with detailed advice.

If we express these results in terms of relative reduction of fuel consumption, the group supported by the extended advice system saved up to 7% of fuel compared with driving without support. Using existing devices, drivers were only able to reduce fuel consumption by 3-4%. Compared with the fuel consumption during 'normal driving', drivers presented with extended advice obtained an average fuel reduction of 16%.

Similar effects with larger fuel reductions were found when driving in urban environment. Figure 4 shows that drivers are quite able to make some reductions in fuel consumption by themselves (run1 -> run 2). However, with support of an advice system, unlike using existing systems, drivers are able to reduce fuel consumption even further. In the urban environment, an additional reduction of 14% was found. Compared with 'normal driving' this yields a fuel reduction of 23%.

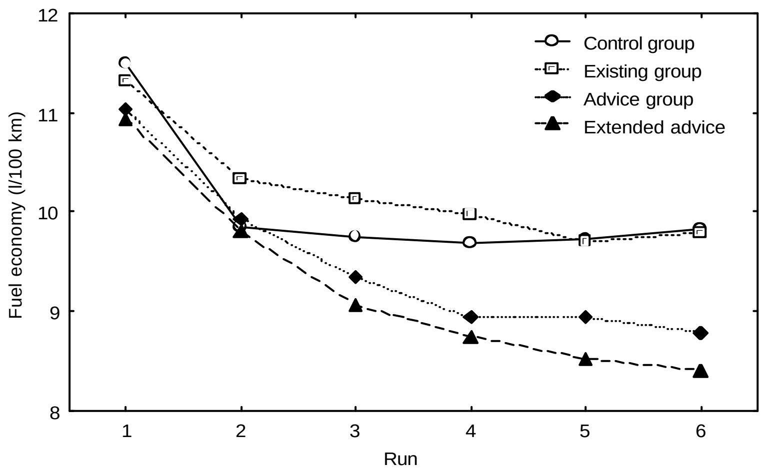

Figure 4 Fuel Economy as a function of Group and Run in the urban environment

Within the rural and highway environment, smaller reductions are obtained. The large impact of the support tool within the urban environment can be explained by the more complex situations and the higher traffic volumes a driver is confronted with in these conditions. Apparently, drivers could use detailed advice on how to drive more fuel-efficiently especially in more complex situations.

During the experiment, participants were instructed to keep trip time constant. Analysis of the average speed over the trip revealed that all drivers had the tendency to reduce speed during the second run and to drive faster during the last two runs. However, the average speed did not differ significantly from the average speed during the first run during any of the runs. In other words, it is possible to significantly reduce fuel consumption without increasing travel time.

Behavioural changes

The analysis of fuel economy has shown that drivers can significantly increase fuel economy when presented with detailed advice. Next step is to evaluate what kind of change in driver behaviour caused this increase in fuel economy. This evaluation was carried out by comparing the two extremes, that is the control group and the group provided with extended advice, with regard to the total number and type of advices generated. An advice generated by the normative model of the fuel-efficiency support tool represents a deviation of actual from optimal behaviour. Therefore, the number of advices generated (not including the number of positive advices) provides an indication of fuel-efficiency, that is the less advices generated the more fuel-efficiently the driver has driven. In addition, the type of advice gives an indication of which actions caused inefficient behaviour. Although the control group did not receive any advice, it was possible to calculate, based on vehicle data recorded during the experiment, the advices that would have been presented when this group had received feedback.

Analysis of the total number of advices generated revealed a significant difference between drivers with and without support during runs 5 and 6 [Median test; $p<0.05$]. This is shown in

Figure 5. For drivers without support the total number remains more or less constant, whereas for drivers with support this number decreases.

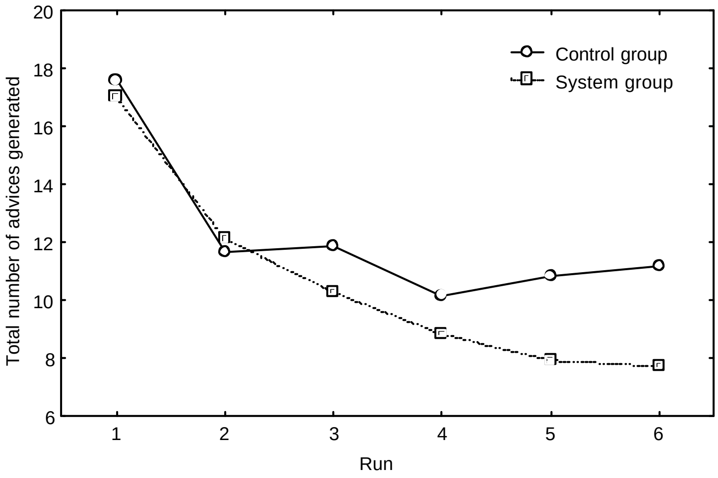

Figure 5 The total number of advices generated as a function of Group and Run.

Next it was investigated which driving characteristics were altered through the use of the fuel-efficiency support tool. No differences in the number of advices between drivers with and without support were found for any of the advice categories Idling, Anticipate, Deceleration, Acceleration and Shifting-during-Cruising over any of the runs. The difference in the total number of advices generated appeared to be totally caused by an impact of the support tool on the number of advices generated within the category Shifting-during-Acceleration. For this category, a marginal statistically significantly lower number of advices was found during run 5 [$p<0.1$] and a significantly lower number during run 6 for the drivers provided with detailed advice than for the drivers without support. Further analysis revealed that drivers without support shifted significantly more times too late from 1st to 2nd gear and from 2nd to 3rd gear than drivers who received support (and drove more fuel-efficiently). No significant differences between the groups were found with regard to shifting from 3rd to 4th gear'.

Furthermore, the number of times drivers were able to drive fuel-efficiently for more than 4 minutes (that is the number of positive advice) was significantly higher for drivers provided with detailed advice than for drivers without support [$p<0.01$].

<u>Secondary effects</u>

Besides the impact of the new fuel-efficiency support tool on fuel consumption, also secondary effects were investigated. First the speed-acceleration relationship was evaluated. Analysis has revealed no change in average speed. On the other hand, fuel economy was significantly affected by gear changing during acceleration. Analysing the speed-acceleration relationship should reveal whether the actual magnitude of acceleration was also influenced by fuel-efficient driver behaviour.

Analysis revealed a decrease in maximum deceleration over the whole speed range between normal driving (run 1) and fuel-efficient driving without support (run 2) for both groups. However, during run 5, the drivers provided with detailed advice showed a further reduction of the number of extreme negative accelerations, whereas drivers without support seem to return to their normal behaviour. Figure 6 shows the speed-acceleration relationship for run 1 and run 5 of the group provided with detailed advice. With regard to positive acceleration, the new fuel-efficiency support tool caused similar effects in the 10-20 km/h speed range.

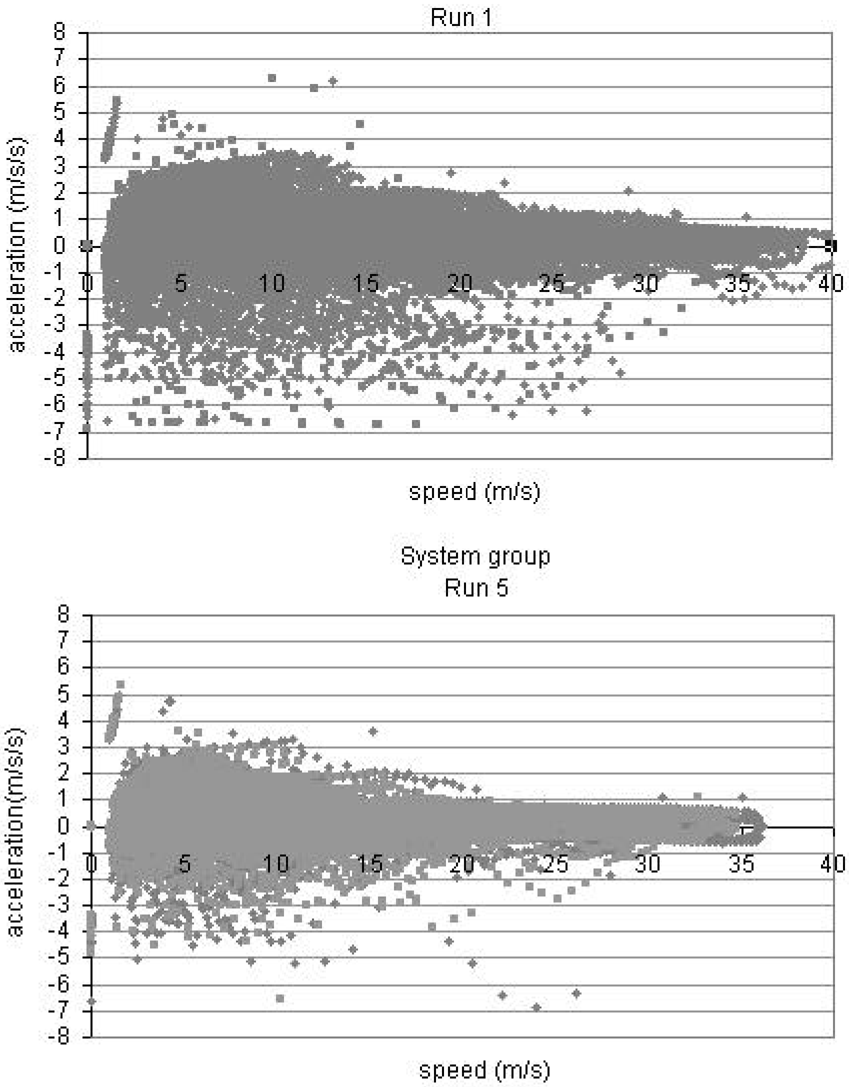

Figure 6 Speed-acceleration relationships

Time-To-Collision was also subjected to analysis in order to reveal a possible secondary effect of fuel-efficient driver behaviour. Time-To-Collision (TTC) is calculated by dividing following distance between two vehicles by their speed difference (4). TTC only defined if vehicle speed is higher than the speed of the preceding car. Since no real interaction between vehicles takes place at TTC's larger than 10 seconds, only the number of TTC-values smaller than 10 seconds was analysed. Within the experiment, TTC-values between 1 to 2 seconds occurred. Analysis of the number of TTC's in this range revealed no differences between drivers with and without support during the second run, that is under equal conditions. During run 5, drivers presented with detailed advice had marginal-significantly less encounters with other vehicles than drivers without support [$p<0.1$].

CONCLUSIONS

A new-generation fuel-efficiency support tool has been designed. The support tool is based on a normative model that identifies the present context of the vehicle and calculates the optimal behaviour within this context. If actual behaviour deviates from the optimal behaviour, the support tool presents advice to the driver on how to change his or her behaviour.

Through a driving simulator experiment, the fuel consumption reducing abilities of this new system have been tested against a control group and existing devices. The experiment revealed that, using the new fuel-efficiency support tool, drivers are able to drive significantly more fuel-efficiently than without support or by using the existing devices. Using the new tool, they achieved, over the combined urban and non-urban cycle, a fuel reduction of 16% compared with ‘normal driving’. Compared with driving fuel-efficiently without support, this implies an additional reduction of 7%. In the urban environment, reductions of up to 23% were achieved.

The behaviour of drivers provided with detailed advice deviates significantly less often from optimal behaviour compared with drivers without support. The reduction in fuel consumption is caused by a change in driver behaviour with respect to gear changing during acceleration: drivers with support accelerate at the same pace, but change earlier to a higher gear than drivers without support.

Also the secondary effects of the new support tool were investigated. Analysis of the speed-acceleration relationship revealed a reduction of the number of extreme negative accelerations that occurred. Therefore, with the new support tool present, drivers seem to anticipate more. This finding is supported by the smaller number of Time-To-Collisions of 1 to 2 seconds that was found for this group compared to drivers without support.

These promising results will be verified on the road in a field trial by means of an instrumented vehicle or fleet study. This field trial will enable us to evaluate the impact of the system in and on real traffic conditions at a microscopic level. The field trial will also be used to assess the effects of the system on vehicle emissions.

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