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A prototype 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. If drivers are prepared to change their driving habits they can complete the same journeys within similar travel times, but using significantly less fuel. In this paper, a prototype fuel-efficiency support tool is presented which helps drivers make the necessary behavioural adjustments.

The support tool includes a normative model that back-calculates the minimal fuel consumption for manoeuvres carried out. If actual fuel consumption deviates from this optimum, the support tool presents advice to the driver on how to change his or her behaviour. To take account of the temporal nature of the driving task, advice is generated at two levels: tactical and strategic.

Evaluation of the new support tool by means of a driving simulator experiment revealed that drivers were able to reduce overall fuel consumption by 16% compared with 'normal driving'. The same drivers were only able to achieve a reduction of 9% when asked to drive fuel efficiently without support; thus, the tool gave an *additional* reduction of 7%. Within a simulated urban environment, the *additional* reduction yielded by the support tool rose to 14%. The new support tool was also evaluated with regard to secondary effects.

Keywords: Fuel efficiency; Normative model; In-vehicle device; Simulator study

1. Introduction

Transport, and road transport in particular, is a major consumer of finite fossil fuel resources. Furthermore, the CO_2 emissions from fossil fuels are widely recognised as highly environmentally

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damaging. A major technological breakthrough or paradigm shift may solve this problem but, because of existing investments, cultural attitudes and remaining technological challenges, such a shift is likely to take a long time. Therefore, fuel conservation, i.e. performing the same (or similar) transport task with the use of less fuel, is a sensible interim strategy.

There are several methods for reducing the fuel consumption of road transport. On a long-term horizon, reductions in fuel consumption can be obtained through new technologies or law and policy. Besides developing alternative fuels, new technology can improve the fuel economy of individual vehicles by an improvement of rolling and air resistance and of engine and transmission efficiency. Law and policy can help by setting goals and standards and by imposing taxes.

On a short-term horizon, factors that can influence fuel consumption include infrastructure changes (e.g., car pool lanes), traffic management and driver behaviour. Congestion and fuel consumption are closely related. An improvement in traffic performance through traffic management or a change in infrastructure will therefore also have a positive impact on fuel economy. Every driver also has an effect at an individual level as manifested in his or her microscopic driver behaviour.

Of the four factors described above, new vehicle technology definitely has the largest potential to reduce fuel consumption. Decicco and Ross (1996) envision a potential saving of 49%. Compared to this, the 5% potential savings subscribed to traffic management and law and policy seem almost negligible. However, as noted above, a major technological change will have a relatively long implementation time. Changes in driver behaviour may therefore be seen as an important factor to emphasise. Waters and Laker (1980) estimate a potential saving of up to 15%; furthermore, driver behaviour is a factor which can induce a significant reduction in fuel consumption in the short term, even starting today. In addition, some savings obtained by changes in driver behaviour may still be valid when new vehicle technology becomes available. Together, they can reduce fuel consumption even further.

2. Driver behaviour

It is a well-known fact that different drivers can obtain different fuel consumption figures for the same car. A number of studies have been carried out to examine and quantify the influence of driving characteristics. Evans (1979) found evidence that by reducing acceleration levels and generally driving more ‘gently’, combined with a skilful avoidance of stops, a driver could reduce fuel consumption by as much as 14% without increasing trip time.

The largest impact of driver behaviour is reported by Waters and Laker (1980). They asked drivers to drive ‘normally’ around a circuit, all using the same car. A difference of 50% in fuel consumption was found between the most and least economical drivers. In a second trial, drivers were asked to drive in a way they considered to be economical. Generally, the drivers interpreted this as driving slowly, but when a correction was made to account for speed differences, there was still a saving of nearly 15%.

Although it is clear that driver behaviour has a significant bearing on fuel consumption, it is often unclear how one should control the car in order to get the best possible fuel economy. Detailed analysis of the relation between driver behaviour and fuel consumption by Hooker (1988) revealed that those elements of driver behaviour related to gear shifting, speed choice and acceleration and deceleration have the greatest influence on the fuel consumed. Based on these insights, advice on how to change driver behaviour in order to optimise fuel economy can be given. Optimisation of fuel economy can, generally, be achieved by driving the vehicle under conditions of high engine efficiency, e.g., by quickly shifting up gears and avoiding high speeds and by anticipating traffic conditions in order to eliminate unnecessary braking. Before discussing possible ways of modifying driver behaviour, one must discuss the question of motivation. Are drivers interested in this issue and willing to try to change their behaviour? Whilst this paper does not attempt to produce a quantitative answer to this question, one can point to several pieces of qualitative evidence which suggests that a significant proportion of drivers are motivated to change their behaviour.

- The increasing popularity of "eco-driving" courses in which people learn to drive more fuel efficiently.
- The existence of a market for earlier-generation fuel efficiency support tools such as vacuum gauges (irrespective of their efficacy).
- General levels of increasing environmental awareness and concern.

2.1. Driver feedback

An optimal driver behaviour exists, which minimises the fuel consumption of a vehicle on a certain trip. Different methods can be used to influence driver behaviour in order to induce this desired behaviour: the driver could be given information and education on how to drive fuel efficiently, the driver could be provided with feedback on the effects of his own behaviour and systems could be installed which overrule the decisions of the driver if they contradict the desired behaviour.

The most viable way to induce the desired behaviour seems to be to provide the driver with feedback. Psychological research by Seligman (1978) suggested that giving immediate feedback to an individual on the effects of his actions enables better control of actions. Furthermore, feedback can not only help to obtain the desired behaviour, but also to maintain it in the long term.

Feedback can be provided to the driver in different forms. An attractive way is to provide the driver with direct feedback in the vehicle by means of a driver support tool. Several driver support tools were developed, after the first oil crisis in 1973/1974, to directly or indirectly improve fuel economy, e.g., manifold vacuum gauges, miles-per-gallon meters, trip computer devices and cruise controls. In general, these devices aim to provide either vehicle acceleration control or vehicle cruise speed control and were reviewed by Hinton et al. (1976). However, tests of such devices revealed that the improvements in fuel economy achieved due to the devices were either insignificant or very small and came in no way close to the 15% improvement judged possible due to a directed, consistent change in driver behaviour; see Barth (1981).

It is believed that the reason for these very small improvements can be found in the sometimes inaccurate, contradictory and unclear information presented to the driver. None of the devices took into account the spatial and temporal context the vehicle was in. Achieving the right level of temporal granularity for optimisation is important; too coarse and many opportunities to improve performance will be missed. Conversely, a fine-grained approach will operate in local optima which may or may not represent the global optimum over a longer period of time. In addition, the devices were often judged to be distracting and irritating, which resulted in them being ignored. These disadvantages were especially present when driving in urban traffic: the situation in which most (excessive) fuel is used.

2.2. User requirements for a fuel-efficiency support tool

Detailed design criteria and comprehensive review material are available in van der Voort (1997). In summary, based on the described disadvantages of existing devices, it can be 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 context a vehicle is in;
- place no requirements on the driver which are too high to combine with the actual driving task;
- work within both an urban and non-urban environment.

One potential way to meet these requirements is to provide the driver with direct information on *how* to drive more fuel efficiently. As inputs to the system, not only variables concerning the vehicle, but also external factors such as current headway and gradient should be considered. This enables contextual feedback to be given to drivers with regard to more parameters and over a more useful timescale.

3. System architecture

Within this research project, a new fuel-efficiency support tool has been designed which takes into account the previously described requirements. In this section, the basic architecture and functionality of the proposed support tool will be described. It comprises three basic components:

1. sensors,
2. data processing module,
3. human–machine interface (HMI).

The proposed system is not a closed-loop control system in that it is purely advisory. The driver can decide whether or not to accept the advice from the HMI.

3.1. Basic architecture

The data-processing module is based around a concept known as a *normative model* (Fig. 1). This model describes the optimal driver behaviour for a wide range of contexts known as *states*, for example acceleration, braking, cruising and descending or ascending gradients. Determination of the current state is a key pre-processing task. Actual driver behaviour is then compared to the optimal behaviour using the normative model and if the difference is large, a non-optimal behaviour is diagnosed. This in turn leads to advice being generated, which is considered for presentation to the driver via an HMI. Whether or when the advice is presented is determined by a scheduler. This scheduler includes a safety check; it is reasonable to assume that safety takes priority over fuel consumption and, therefore, advice may be cancelled if issuing it could lead to a dangerous situation developing.

The architecture of the normative model is a multi-layered construction. The lowest layer is known as the *tactical* level and is based on recent measurements. The next level up is known as the

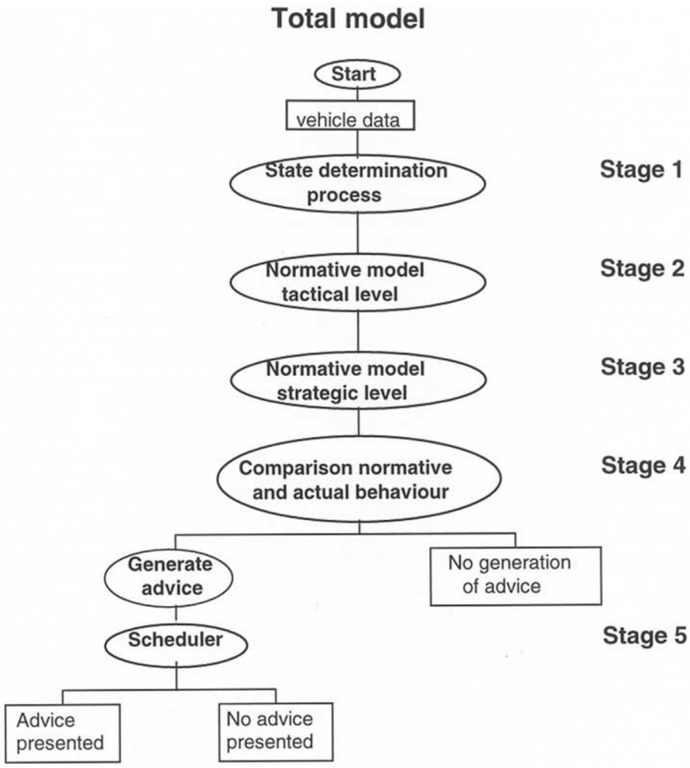

Fig. 1. Total model diagram.

strategic level and uses a longer history of recorded measurements to gain a temporal context. These two layers have been designed and a prototype implemented within a driving simulator. They are therefore described in this paper. It is anticipated that a third layer could be added to the system, which consists of learning and prediction. This would extend the time dimension into the future. The data processing module is of critical importance and is described in greater detail in the next section of the paper. In the remainder of this section, the sensors and HMI components will be briefly described. We also discuss system parameters.

3.2. Sensors

As far as is possible, any fuel-efficiency support tool should use inputs which are readily available from existing in-vehicle systems and technology. This avoids the need to install many specialised sensors, which could add considerably to the cost of both initial installation and maintenance. We therefore only used the following variables as inputs to the system:

- speed of vehicle,
- rotational velocity of engine,
- clutch (binary in/out),
- gear position,

- gas pedal position,
- braking force,
- steering angle,
- headway.

In the driving simulator experiment carried out, these variables were sampled three times per second. This sampling rate is used as the base clock cycle for the data processing modules.

In fact, for a car with manual transmission, the gear position and clutch variables are redundant, provided data are available on the gear ratios of the car. The ratio of engine speed to road speed is a particular constant when a certain gear is engaged, but tends to vary if the clutch is depressed or the gearbox is in neutral, apart from the obvious case of the vehicle being stationary. The reader should note that we have largely concentrated on cars with manual transmission, since they represent the vast majority of cars sold in Europe. The system we describe could be adapted to a car with automatic transmission without too much difficulty, though.

Steering angle and headway are not major factors in determining fuel consumption *per se*. However, a crude measurement of steering angle helps to isolate events having a significant bearing on fuel consumption, e.g., overtaking or braking for a sharp corner. Headway is an important measurement if one wishes to determine whether the proposed advice is safe and sensible to give to the driver. For example, telling a driver to accelerate harder when there is a slower vehicle in front is counter-productive and could be unsafe. Headway could well be available if the car is fitted with an intelligent automatic cruise control or collision warning device. This is a good illustration of the benefits of an integrated open architecture for in-vehicle telematics systems. We have therefore included headway as an input to the support tool.

The system can be substantially improved if other data are available which give greater contextual resolution. In particular, a variable like gradient would be extremely useful. Gradient is an important variable for optimising fuel consumption, as reported by Hooker (1988). This is because changing the gradient changes the effective rolling resistance of the vehicle (where rolling resistance refers to the component of resistance which is directly proportional to the speed of the vehicle). However, gradient will not be included within the scope of this paper.

3.3. Outputs and HMI

Two HMI's have been designed. They present advice visually to the driver on a 6-in. TFT screen next to the steering wheel. The interfaces differ in the length of advice presented. A distinction is made between advice and extended advice. In the case of 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 Fig. 2. The presented advice is accompanied by an indication of the extent of deviation between actual and optimal driving behaviour by means of green, orange and red LED's. Different LED's can therefore accompany the same advice. For instance the advice to shift earlier will be shown with an orange LED if the driver is only 10 s late, but will be shown with double red LED's when 2 min late.

Fig. 2. The human–machine interface for extended advice.

3.4. System parameters

As well as measured variables, the proposed system requires various parameters to be set. These can be separated into two classes. The first class compensates for the fact that different types of car have different characteristics; if the system is going to be installed in a range of vehicles, it will have to be adjusted accordingly. Important parameters of this type are:

- gear ratios (although, as mentioned above, these share a redundancy with gear position);
- fuel consumption map of the engine;
- vehicle weight;
- rolling- and air-resistance curves plotted against speed.

The fuel consumption map is the key to the whole system. It is a three-dimensional plot of specific fuel consumption versus rotational velocity versus engine torque. It is usually represented in two dimensions by plotting equal specific fuel consumption contours on a graph which has the other two variables as axes. An example of such a map is shown in Fig. 3. Specific fuel consumption is

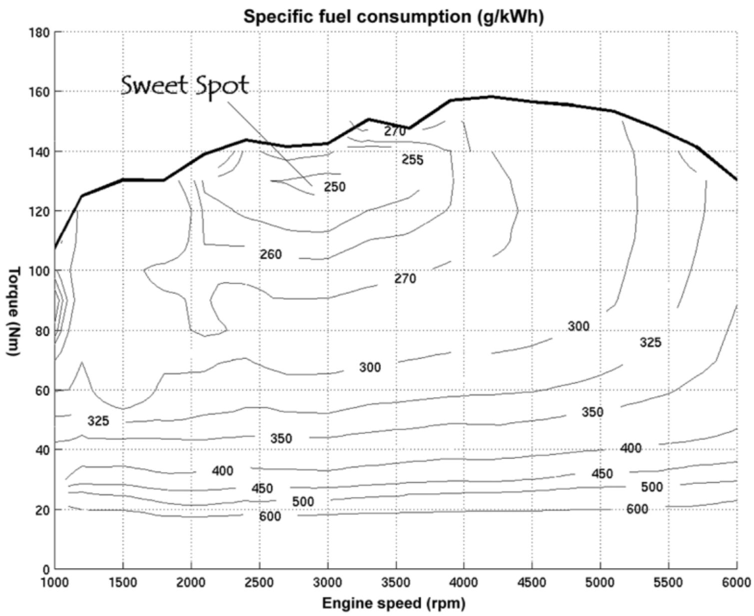

Fig. 3. Fuel consumption map.

the quantity of useful energy supplied per unit of fuel consumed. Thus, the lowest point of this contour map represents the optimum operating point of the engine and is known as the *sweet spot*. The thick black boundary represents the limit of operation of the engine. 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. Note that it is not possible to operate a vehicle at the sweet spot continuously for two reasons:

- the fixed gear ratios of the car mean that for a given road speed, only a finite number of rotational velocities of the engine are possible;
- the sweet spot is at a point where a typical engine produces a quite high absolute level of power; larger than is required during normal cruising.

The second type of parameters is used to tune the behaviour of the system. Typical examples of such parameters are speed limits, minimum "driveability" characteristics acceptable to an average driver, how long advice should be displayed and reasonable speeds for curves of different radii. In general, most of these parameters of the second type could either be user-adjustable or constant across all vehicles; the modelling methodology is sufficiently general and dynamic to cope with variations in such parameters.

4. The data processing module

The top-level architecture of the data processing module has already been described in the previous section. The reader is also referred to the schematic shown in Fig. 1. In this section, each of the elements within this figure will be described in greater detail.

4.1. State determination process

The first step in the data processing module is to pre-process the raw data. The object of this pre-processing is to determine the current *state* of the vehicle. Typical states are cruising, stationary, decelerating, etc. This is necessary because optimal driver behaviour depends heavily on the context in which the vehicle is being driven, and, therefore, different rules and advice are needed. Determining the state is a useful way of categorising the current context.

Fig. 4 shows the complete state-determination process. It works hierarchically from top to bottom. For example if the criteria for reversing are met, the vehicle is considered to be reversing regardless of whether any of the criteria for states lower down the diagram are met. There are various internal parameters which need to be set. Most of these were determined based on literature. For instance, the minimum steering angle beyond which the vehicle is considered to be turning is described by an equation used to determine the curve radius in a road with a certain speed limit. However, to determine the minimum acceleration and deceleration thresholds, which form the boundaries between these respective states and steady cruising, a small driving simulator experiment was held. In this experiment, the magnitude of speed differences that can still be perceived by a driver was revealed.

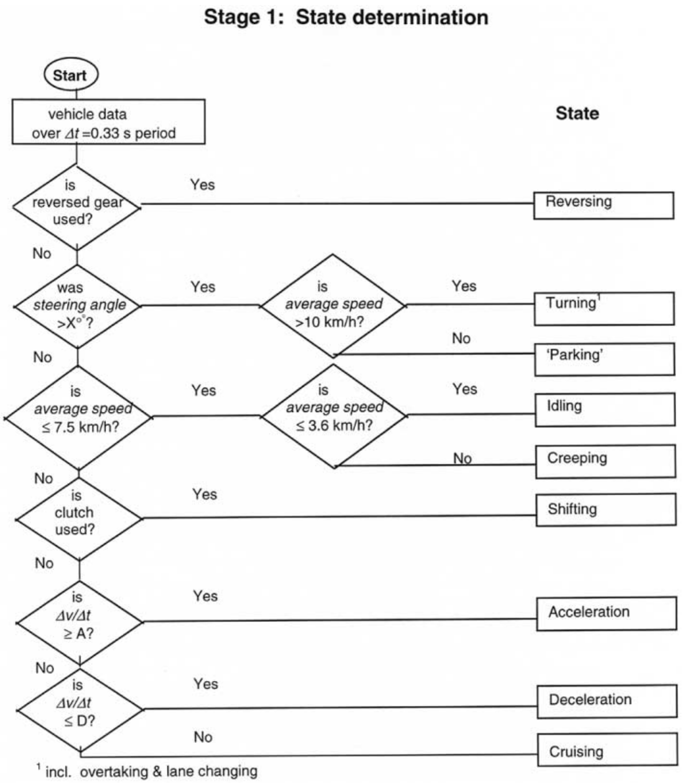

Fig. 4. State-determination process.

4.2. Normative model: tactical level

The tactical level of the normative model is concerned only with the immediate past. 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 change took place. A series of identical states is therefore grouped together and defined as a *manoeuvre*. The unit of analysis for the tactical model is normally a single manoeuvre. However, an exception is made concerning the shifting state. If the states immediately before and after are the same, the shifting will be ignored and the entire sequence allocated to the manoeuvre which encloses the shifting.

For each type of manoeuvre, a normative model of optimal behaviour for minimum fuel consumption has been developed. Space limitations prohibit a full description of these models, but they are based on the following principles.

1. The power profile needed to carry out a given manoeuvre (and associated fuel consumption profile for the engine) is calculated.
2. If no power is needed, it is assumed that the engine could have been declutched, for example, when approaching a stop or when stationary. In this latter case it can often prove advantageous to switch off the engine. A previous paper by Dougherty (1997) discusses this issue.

3. A check is made as to whether the gear in use was the optimum gear. This is done by calculating the fuel consumption from the fuel consumption map and comparing it with what it would have been if a different gear had been used.
4. For manoeuvres which involve acceleration or deceleration, whether better fuel consumption could have been achieved by changing the rate of acceleration/deceleration is examined.
5. Excessive speed is discouraged.
6. "Smooth" use of the accelerator is encouraged, particularly when cruising.

During cruising, the driver has few options available to save fuel; the main principle is that fuel consumption follows a classic U-shaped curve, with a minimum in top gear typically around 70–80 km/h. Thus, choice of speed is the main factor which affects fuel consumption. Furthermore, the gear position is of great importance, especially at lower speeds. Smooth use of the accelerator also helps to minimise fuel consumption.

However, particularly during acceleration, choice of gas pedal trajectory *through time* and appropriate gears (items 3 and 4 in the above list) become important factors. In other words, to get optimum fuel consumption, it is not enough to solve the problem of minimising fuel consumption instantaneously; it has a temporal dimension. To calculate the optimal normative behaviour, extensive use of the fuel consumption map is made. The algorithm used works according to the following principles. Acceleration requires additional energy to be supplied from the engine and converted into kinetic energy. The driver determines the rate at which this energy is supplied, by controlling the power output of the engine. It makes sense to let the driver produce an amount of power which allows the engine to operate close to the sweet spot, i.e., where specific fuel consumption is minimised. Formally, for a vehicle in a given gear and driven with a certain velocity, the engine has fixed rotational velocity. Therefore, the driver can operate the engine at any point on the vertical line that represents this rotational velocity on the fuel consumption map. Since the map is monotonic decreasing, there will always exist a minimum specific fuel consumption. This can be back-converted into the appropriate accelerator position. As the vehicle accelerates, the rotational velocity of the engine increases and a new minimum fuel consumption, with associated accelerator position, can be calculated. Thus, a trajectory of optimal accelerator position can be produced.

The above description does not refer to changing gear. This is dealt with in the model by simultaneously calculating what the minimum fuel consumption would be in the other gears to produce a similar amount of power. If this fuel consumption is less than the fuel consumption in the current gear, it implies that the optimal moment to change gear has arrived. Note that driveability considerations mean that the driver would not be happy to change gear if this meant insufficient power available to complete the manoeuvre in a smooth fashion; this neatly constrains the model to a single solution. This aspect of the model is illustrated in Fig. 5, which is a schematic of the normative model for acceleration.

4.3. Normative model: strategic level

The strategic level consists of a set of rules which have been derived from the studies concerning optimum fuel consumption referred to in this paper.

1. Do not start a trip idling the engine.
2. Do not idle the engine for more than 15 s; turn it off.

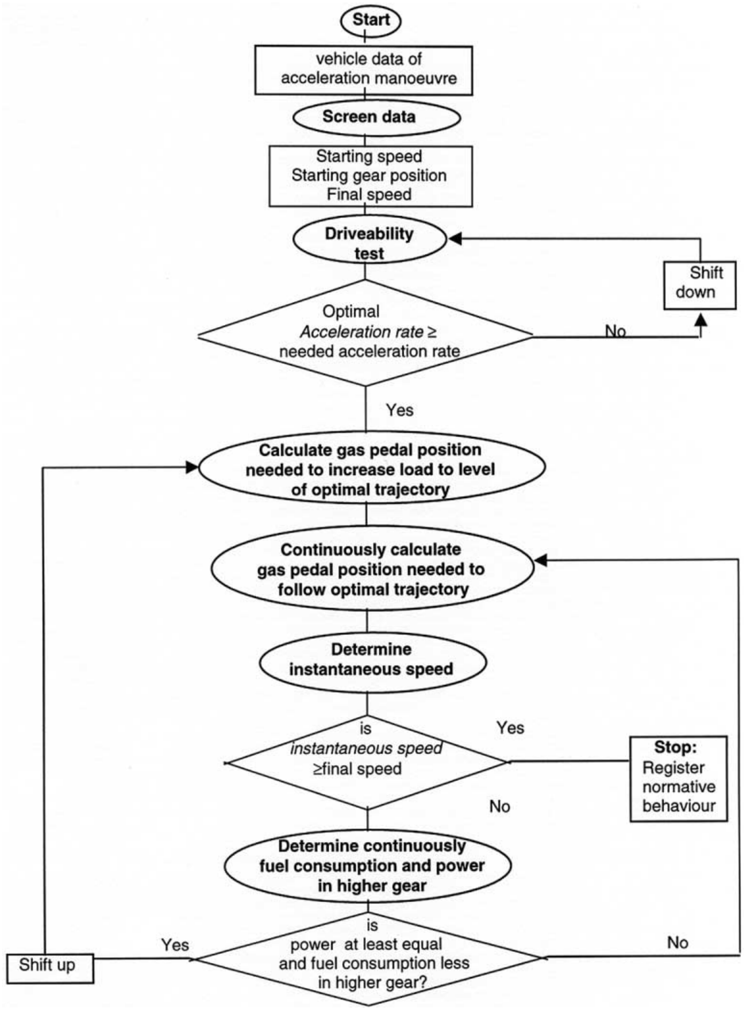

Fig. 5. Normative model for acceleration.

3. Do not creep and idle for more than 20 s in total.
4. Braking at emergency level should not occur more than twice per hour.
5. Acceleration should not be closely followed by deceleration.
6. Deceleration should not be closely followed by acceleration (unless you are turning).
7. Overtake only if you can gain your intended cruising speed soon afterwards.

These rules (and associated sub-rules which provide the logic to detect the events described) are implemented as finite automata within the prototype system; details are in Dougherty and van der Voort (1999). Some of these rules might imply slight changes in strategic driving behaviour. For example, rule 7 might result in advice not to overtake a long chain of vehicles one at a time over an extended period. This is probably good advice if one wishes to minimise fuel consumption, but it may not be advice which drivers wish to accept.

4.4. Advice generation

The next step of the data processing module is the generation of advice to the driver. This is done by comparing actual behaviour against normative optimal behaviour. Both tactical and strategic levels have advice generators, and a separate generator exists for each defined manoeuvre. This is best illustrated with reference to the advice generation flow chart for acceleration, which appears as Fig. 6. Note that this manoeuvre was used to illustrate the tactical level of the normative model; see Fig. 5. The flow chart contains various parameters and variables which need explanation.

- X represents the allowed deviation between optimal and actual behaviour before advice is generated. The value can be adjusted, for instance, in time. A learning driver could be helped with more advice. Therefore X should be set low. For a more advanced driver, this value could be increased. This would also help the acceptance of the driver.

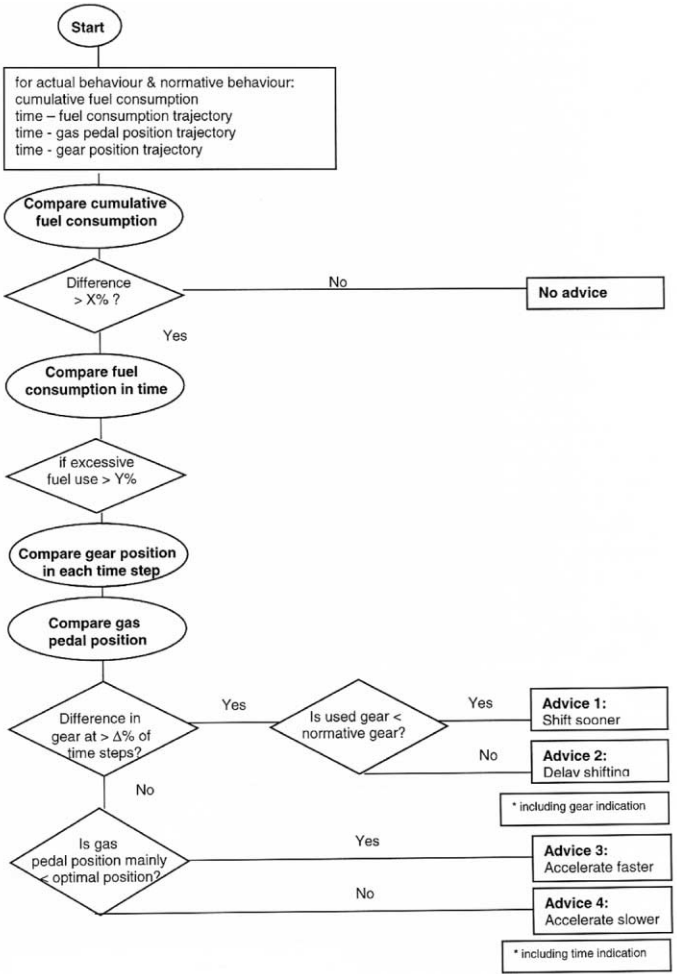

Fig. 6. Advice generation for acceleration.

- Y is used to identify the timestamp in which excessive fuel use occurred.
- Delta represents the importance of gear position above gas pedal position within the model. Delta is therefore set to a value smaller than 50%.

The strategic advice system works in a similar way but, as described previously, it concentrates on identifying particular pre-defined sequences of manoeuvres. Each of these sequences is, in general, linked directly to a piece of advice. To avoid presentation of negative advice only, positive feedback is provided to the driver after driving fuel efficiently for more than four consecutive minutes. If advice is triggered, this is passed through to the scheduler sub-system for possible presentation to the driver.

4.5. Scheduler

Before the generated advice is presented to the driver, it first goes into the scheduler sub-system. This scheduler has two functions:

(a) *Timing of advice*: To ensure that different pieces of tactical and strategic advice do not obviously conflict within a short period of time, which could prove confusing to the driver.

(b) *Safety check*: To check (as far as is possible) that a particular piece of advice is not dangerous within the current driving context. For example, advising a driver to accelerate harder when the current headway is too small or during emergency braking.

If the safety check is negative with respect to the content of the advice, the advice is not presented. If the timing of the advice is not appropriate, it will be stored in the buffer of the scheduler and reconsidered after a 1-s period.

5. Results from the simulator experiment

The new fuel-efficiency support tool was evaluated with regard to its ability to reduce fuel consumption through a driving simulator experiment. The experiment was carried out at the TNO Human Factors Research Institute in The Netherlands. Their driving simulator consists of a moving base mock-up with normal controls and, in this experiment, a manual four-speed transmission. A computer-generated image system is used to generate the visual scene. The image is projected on a screen with a visual angle of 120° (horizontal) and 35° (vertical) in front of the mock-up. An impression of the scene during the experiment is shown in Fig. 7. More details of the driving simulator can be found in Hogema and Hoekstra (1998).

In the experiment, the advice system with each of the interfaces was judged against an existing system and a control group. The existing system was related to the miles-per-gallon meter. It showed, every three minutes, the average fuel consumption over the previous 3-min period, expressed in litres per 100 km. In addition, an indication of fuel efficiency was giving by means of green, orange and red LED's. This indication was calculated by dividing the actual average fuel consumption by the general average fuel consumption for that vehicle.

In total, 88 male subjects participated, equally divided over four groups, that is, the Control group, Existing group, Advice group and Extended advice group. Each participant drove six runs through urban, sub-urban and highway environments. The total distance of the trip was 18 km. Of these 18 km, roughly 5, 7 and 4 km were designed as, successively, urban, sub-urban and

Fig. 7. Driving simulator and experimental environment.

highway environments. The first run consisted of normal driving. In the second run, the participants were instructed to drive as fuel-efficiently as possible whilst keeping trip time constant. During Runs 3–6, the participants were again asked to drive fuel-efficiently, only this time – with exception of the control group – receiving feedback from the support tool assigned to them; the Control group received no form of feedback during the experiment. The Existing group received support from the existing device during these runs. The new support tool presented basic advice to the drivers in the Advice group, whereas the Extended advice group received detailed advice from this tool during these runs.

5.1. Effects of the tool on fuel consumption

Comparison of the fuel economy (measured over the total trip in l/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.

During Runs 3–6, significant differences between the groups were found (Kruskal–Wallis ANOVA; $p < 0.005$). Fig. 8 shows the main effect of group on the average fuel economy during Runs 3–6 over the whole urban–sub-urban–highway cycle. A post-hoc multiple comparison (Tukey HSD) showed that the group supported by the extended advice system drove *significantly*

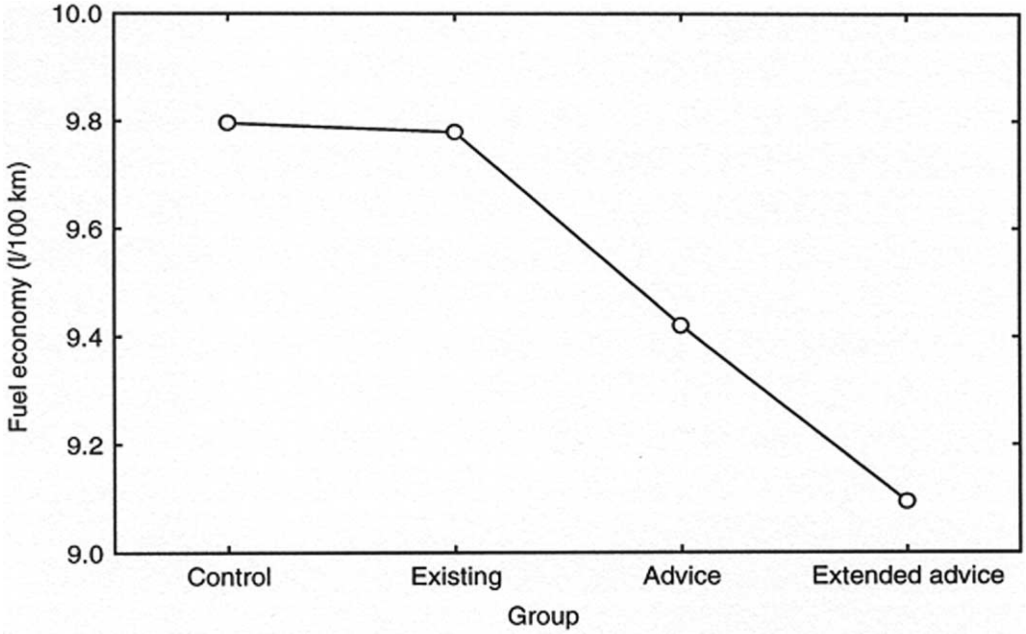

Fig. 8. Effect of group on fuel economy (l/100 km) for the total journey.

more fuel-efficiently, compared with both the control group and with the group supported by the existing systems ($p < 0.01$). No significant effect due to 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% fuel compared with their fuel consumption while driving fuel-efficiently without support (Run 2). Using existing devices, drivers were only able to reduce fuel consumption by an additional 3–4% compared to no support. Compared with their 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 a simulated urban environment. Fig. 9 shows that drivers are quite able to make some reductions in fuel consumption by themselves (Run 1 → Run 2). However, with the support of an advice system, unlike with 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%.

Within the rural and highway environments, 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.

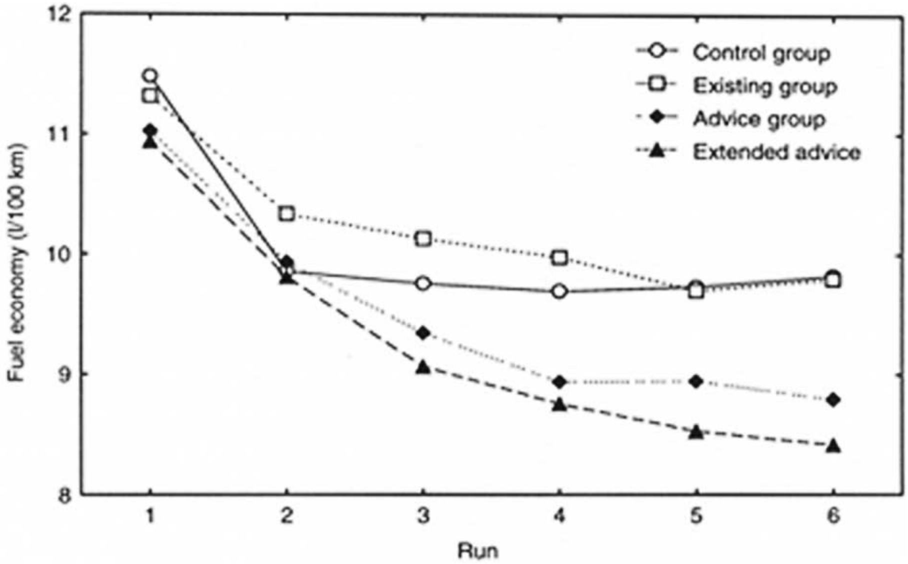

Fig. 9. Fuel economy as a function of group and run in the urban environment.

During the experiment, participants were instructed to keep trip time constant. Analysis of the average speed over the trip revealed that all drivers had a 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 (Tukey HSD test). In other words, it is possible to reduce fuel consumption quite considerably without noticeably changing travel time.

Analysis of generated advice revealed that the reduction in fuel consumption is mainly caused by an adjusted gear-changing behaviour during acceleration: drivers change earlier to a higher gear, especially from 2nd to 3rd gear.

5.2. Secondary effects

Besides the impact of the new fuel-efficiency support tool on fuel consumption, secondary effects were also 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 altering the way gear changing during acceleration was carried out. Analysing the speed–acceleration relationship should reveal whether the actual magnitude of acceleration was also influenced by fuel-efficient driver behaviour. This in turn could affect the overall behaviour of traffic streams.

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 seemed to return to their normal behaviour. With regard to positive acceleration, the new fuel-efficiency support tool caused similar effects in the 10–20 km/h speed range.

Time-to-collision (TTC) was also subjected to analysis in order to reveal a possible secondary effect of fuel-efficient driver behaviour. TTC is calculated by dividing the following distance between two vehicles by their speed difference; see van der Horst (1990). TTC is 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 s, only the number of TTC values smaller than 10 s was analysed. Within the experiment, TTC values between 1 and 2 s were observed. 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 marginally less encounters with other vehicles than drivers without support (Kruskal–Wallis ANOVA; $p < 0.1$).

6. Conclusions and future work

This paper has presented a prototype fuel-efficiency tool. A driving simulator experiment has shown that, using the tool, drivers improve fuel consumption significantly and that these substantial savings can be obtained without significantly changing journey times. The highest improvement in fuel consumption was achieved in urban situations and seems to be caused by an adjusted gear-changing behaviour during acceleration. Important secondary effects are a reduction in incidences of extreme acceleration and deceleration and small TTC's. This could improve throughput and reduce accidents.

The next stage of our work is to field test a prototype of the tool in an on-street situation using an instrumented vehicle. An interesting spin-off from this work will be the provision of useful evidence as to the efficacy of carrying out driving simulator experiments to investigate the effect of driver behaviour on factors such as fuel consumption and pollution. A further important aspect that will be investigated is whether the majority of drivers will be motivated by the tool to maintain good driving habits in the long term. The impact of the support tool on traffic performance and traffic safety will also be analysed using a microscopic traffic simulation model.

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