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ANALYSIS OF A DRIVER BEHAVIOUR IMPROVEMENT TOOL TO REDUCE FUEL CONSUMPTION

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Abstract— A number of technologies have been introduced into new automobiles with the aim of reducing CO₂ emissions. One method of improving fuel consumption is to improve driver behaviour, since eco-driving techniques can help save 10-15% of fuel. A retro-fittable driver behaviour improvement device has been developed and tested in real world conditions. The device provides real-time audio and visual feedback to the driver to improve his/her driving style. It was tested on 15 vans belonging to various companies in the UK and over 39,000km of data was collected. It was observed that use of the device saved an average 7.6% of fuel. Further analysis showed that the savings were obtained as a result of improvement in driving behaviour through reduction in harsh accelerations and early gear shifting into higher gears. There was also a reduction in the pedal busyness of drivers with the system fitted. A model was created using the data obtained to predict the fuel savings that can be achieved if the device is fitted onto a new vehicle.

Keywords- driver behaviour, fuel consumption, fuel savings, driver support, driver feedback, eco-driving, retro-fit

I. INTRODUCTION

Increasing fuel costs, depleting fuel reserves and rise in CO₂ emissions have accelerated the development of automotive technologies. A number of advanced vehicular technologies have emerged in the past decade, but little focus has been given to driver behaviour improvement for fuel consumption benefits. Technologies aimed at reducing fuel consumption and exhaust emissions take time to be adopted by all manufacturers, thus their impact and payback time to the consumer will be close to a decade [1]. Concentrating on driver behaviour helps to reduce fuel consumption in the short-term [2]. The Transport and Road Research Laboratory suggests 10-15% fuel savings are possible by modifying how drivers control their vehicle [2]. An added advantage of driver behaviour improvement is that, on the development of a new technology, most of the improvement made through driver behaviour changes would be preserved [3].

A number of eco-driving courses where a driver is taught to drive moderately have been described in the past. Beusen *et al.* [4] conducted experiments on a sample of 10 drivers for a period of 5 months before and after the course and observed a fleet reduction in fuel consumption of 5.8%, but by the end of the trial most of the drivers tended to return to their original

driving habits. Van der Voort [3] developed a driver support tool that helped drivers improve their driving style and conducted simulator tests and a field experiment. The tool was shown to have reduced fuel consumption by 11%. De Vlioger [5] conducted tests on a total of 10 cars where drivers had to drive calmly, normally and aggressively. It was concluded that aggressive driving which involved sudden accelerations and braking caused fuel consumption to increase by 40% and emissions to increase four fold compared to normal driving. According to Alesandrini *et al.* [6], fuel consumption not only depends on vehicle speed and drive cycle, but also on pedal usage. It was also noted that drivers use the throttle pedal independently of the drive cycle, as different drivers were shown to have different throttle positions and driving styles in the same traffic conditions.

Another important factor in eco-driving is early gear shifting. From simulations by Van der Voort, it was seen that shifting earlier into a higher gear accounted for most of the savings when the driver support tool was tested [3]. It was also observed by Vagg *et al.* [7] that changing gear shift points in the New European Drive Cycle (NEDC) saved 3.6% of fuel consumption.

One of the major weaknesses identified with previous literature was the fact that drivers knew they were being tested to understand the link between fuel consumption and driver behaviour, which may have caused them to be more conscious during their baseline testing phase, thus skewing results. Identifying strengths and weaknesses of the previous literature, a new driver behaviour improvement system was developed to provide real time feedback to the driver.

II. THE SYSTEM

A. Overview

The system provides real time visual and audible feedback based on the driver's performance. Information recorded from the vehicle is processed by the device and a report is also sent to the fleet manager who can then rank the drivers based on their performance. Figure 1 shows the driver display of the device which is fitted inside the existing instrument panel of the vehicle. It consists of two sets of light emitting diodes (LEDs) showing short term and long term driver performance.

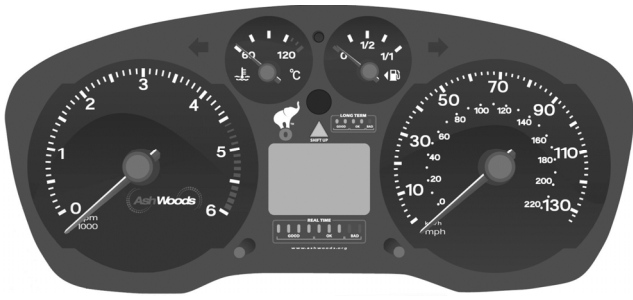


Figure 1. Device instrument panel display

There is also an upshift indicator light in the shape of a triangle which asks the driver to shift to a higher gear. Audio warnings are played back to the driver whenever required to communicate the need to improve driving behaviour. The main advantage of the system is that the drivers are constantly reminded to improve their driving style and unlike a passive system, this will not allow them to fall back to their original driving behaviour.

B. Device Design

The algorithm was developed using Matlab/Simulink and was converted to C code using Real-time Workshop before installing onto the vehicle. The factor chosen as a measure of driver aggressiveness was Inertial Power Surrogate (IPS), which is the product of vehicle speed and acceleration. Vagg *et al.* described the system in more detail elsewhere [8]. The system takes in various inputs from the On-Board Diagnostic (OBD) messages available on the vehicle's Controller Area Network (CAN) and processes this information to provide visual and audible guidance to the driver. A set of 9 LEDs show the instantaneous IPS. A moving average of this value gives the long term IPS (IPS_{LT}), which controls another set of 5 LEDs. The value of IPS_{LT} with respect to various thresholds set in the algorithm of the device gives audible warnings to the driver. The driver is given penalties if the audible warnings are ignored.

The system also features a gearshift indicator asking the driver to shift up a gear when it detects the driver is not driving economically. The gear shift indicator algorithm takes into account a number of key vehicle parameters before signaling to the driver to shift up a gear. Parameters including vehicle speed, pedal position and acceleration are used to identify the vehicle's instantaneous mode of operation. According to the identified mode of operation a suitable engine speed is chosen as a threshold, above which the driver is asked to shift up a gear. The system is also capable of identifying the vehicle's gear ratios real-time and adapting the strategy accordingly, thus making it suitable for any vehicle with minimal engineering input. The gear shift indication is conveyed to the driver by a green triangular LED on the display. It also sounds a beep when ignored, which gives the driver an audible warning.

Captured data is processed by the device and a report with information including distance travelled, average fuel consumption, number of warnings received etc. is sent to the

fleet manager of the company that owns the van, who can assess each driver's performance and rank them accordingly. This accountability is an essential aspect of the system if improvements are to be widespread and sustained.

III. FIELD TRIALS

The system was tested on 15 light commercial vehicles for over 4 weeks. The first two weeks of testing involved collecting data from the vans when the device was present in the vehicle with the audio and visual feedback turned off. During this trial the drivers were unaware of the device as the dashboard display was not fitted. This phase collected their naturalistic driving behaviour and this phase shall henceforth be called the '*baseline trial*'. At the end of the baseline trial, the interface display was fitted onto the dashboard and the system was activated. During this trial, both audio and visual feedbacks were communicated to drivers. The active phase shall be called '*interface trial*' in the report. The interface trials were on going for two weeks. In total, the data collected from the 15 vans represented 39,000 km of real world driving, which equated to 1,107 hours from 5,587 separate trips.

The system works by taking inputs from the vehicle CAN and processing the information to understand the driving behaviour of the drivers. The ECU fuel injection rate was used to calculate fuel consumption. Each vehicle ECU has its own calibration error, thus comparing absolute fuel consumption figures among different vehicles was avoided, but the fuel consumption during baseline and interface trials of each van were compared against each other to obtain the net fuel savings.

IV. RESULTS

The results collected from the vans were post-processed and analysed to understand the driving behaviour of the drivers. Fuel consumption was calculated as the litres of fuel used for 100 kilometres (L/100km) of distance travelled. As mentioned above, the absolute values were not compared between vans for two reasons; one being the likelihood of a small calibration error for a particular ECU and the other being the fact that vans from different companies had different drive cycles and purposes. The percentage savings in fuel used was the intended result. Fuel consumption patterns were analysed on a daily basis and reports were then sent to customers.

The use of the system showed a reduction in the fuel consumption for all the vans tested. It also showed an overall reduction in engine speed and throttle activation. It was decided to remove any idling of vehicles above 90 seconds from the dataset, as this corresponds to the 97th percentile of idling time for all the vans and had the effect of distorting results. This made comparing the vans against each other more straightforward. Table 1 shows the average savings over the entire range of tested vehicles. It is evident that the device contributes to reducing driver aggressiveness. The results suggest that drivers tend to drive in a calmer manner with lower engine speeds and earlier shifts when compared to their normal driving behaviour.

TABLE I. PERCENTAGE CHANGE IN VARIOUS PARAMETERS FOR EACH OF THE 15 VANS

	Engine Speed	Average Acceleration	Average IPS	Fuel Consumption
Van 1	-5.54	-13.43	-4.41	-9.16
Van 2	-9.66	0.10	-7.12	-0.43
Van 3	-14.76	-13.16	-21.39	-12.03
Van 4	-18.88	-7.84	-17.07	-11.08
Van 5	-10.04	-21.61	-19.46	-9.89
Van 6	-14.50	-7.93	-11.25	-1.75
Van 7	-7.78	-13.79	-13.03	-8.97
Van 8	-6.34	-18.55	-21.59	-11.82
Van 9	0.51	-14.69	12.45	-8.48
Van 10	-9.90	-6.65	-11.43	-3.44
Van 11	-7.74	-1.93	-5.26	-1.53
Van 12	-12.44	1.37	4.88	-2.75
Van 13	-1.21	-4.01	3.50	-5.25
Van 14	-8.76	-5.68	-8.90	-3.82
Van 15	-8.09	-6.84	-2.66	-8.84

A decrease in IPS suggests that less tractive work is done per unit distance travelled for the interface trial when compared to the baseline trial. Since the reduction in engine speed corresponds to a reduction in fuel consumed by the vehicle (for similar tractive work), it suggests that the engine is now operating at a more efficient point in the engine map. The reduction in average acceleration values show that drivers tend to accelerate more gently to achieve the same speeds as they did during the baseline trial periods and the reduction in inertial power surrogate is understood to be linked in a similar way. Table 2 shows the percentage savings for selected variables between the baseline and interface trials. A reduction in metrics

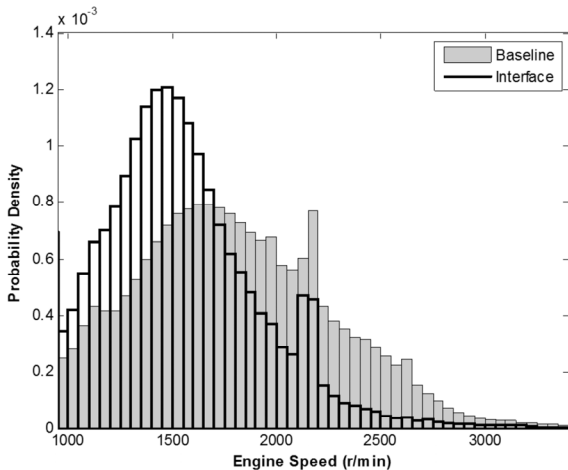


Figure 2. Probability distribution of engine speed (Baseline vs Interface)

TABLE II. CALCULATED RESULTS FROM TEST DATA FOR ALL VANS

	Baseline	Interface	% Change
Fuel Consumption (L/100km)	9.68	8.94	-7.64
Engine speed (rpm)	1748	1513	-13.44
Pedal position (%)	17.30	14.60	-15.60
Inertial Power Surrogate (m^2/s^3)	7.50	6.27	-16.40

such as average engine speed, acceleration and inertial power surrogate can be seen between the baseline and interface trials, all of which contribute to a reduction in fuel consumption.

Figure 2 shows the distribution of engine speed for all the vans tested. Idling engine speed of 800r/min was included in the calculation for the histogram, but the figure was truncated at 950r/min since as previously discussed there was a high concentration of idle data compared to the other engine speeds. It can be seen that there was a clear shift towards the lower engine speeds for the interface trial. One of the major contributors to this reduction is the presence of the gearshift indicator, asking the driver to shift up at appropriate points. The concentration of data points at the 2200r/min corresponds to 100km/hr in 6th gear for the vans. Most of the vans tested were electronically limited to 100km/hr. All the evidence suggests that the drivers tend to become smoother in their driving behaviour by reducing harsh accelerations and shifting earlier into higher gears.

V. ANALYSIS

Analysis of the data collected during the trial is divided into two stages. The first involved analysis to understand the driving patterns and fuel consumption improvement amongst the drivers, whilst the second stage involved creating a simple model to predict the fuel consumption benefit a customer would receive if the device was used in their vehicle.

A. Analysis of Driver Behaviour

Further analysis was carried out on the data to understand where and how the savings in fuel consumption were achieved. Some of the factors of analysis were chosen from experiments conducted by Ericsson [9]. The parameters short-listed for further analysis were relative positive acceleration, inertial power surrogate, specific work done and pedal busyness. Relative positive acceleration is the integral of the product of speed and positive acceleration over the total distance [10]. Specific work was the energy used per kilometer, calculated assuming a constant frontal area and mass for every van.

Figure 3 shows the cumulative probability distribution of the inertial power surrogate. To obtain this plot, deceleration values and idling cases were ignored, otherwise the graph would start at a much higher ordinate value. The y-intercept value in the plot now corresponds to cruising. A shift toward

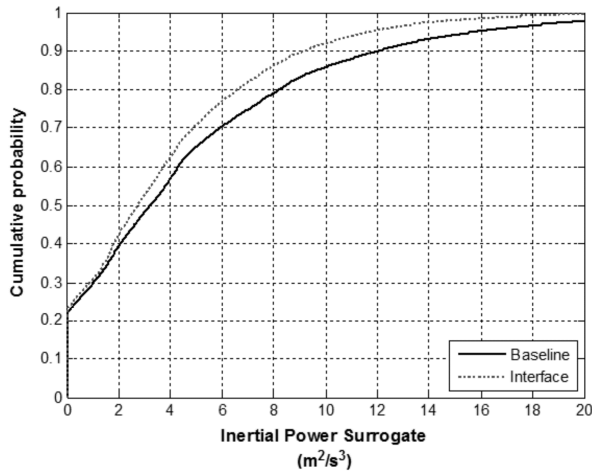


Figure 3. Cumulative probability for Inertial Power Surrogate

the left of around $2\text{m}^2/\text{s}^3$ during the interface trial shows the effect of the device in operation. During the interface trial a shift to the left of the graph indicates a reduction in IPS, which is due to a decrease in harsh accelerations. This suggests that drivers' behaviour was smoother and less aggressive when compared to the baseline trials. Analysis of this pattern helped understand that the reduction in the time spent at higher values of acceleration and inertial power surrogate had a significant impact on fuel consumption.

When the acceleration profiles were observed, similar patterns were noted. Figure 4 shows the acceleration and deceleration histogram for baseline and interface trials for all vehicles. The plot has all idling deleted from it to avoid a large spike at zero when the vehicle is stationary. It was seen that there was a shift from higher acceleration values to lower ones (from 2 to $3\text{m}/\text{s}^2$ to 0.5 to $1\text{m}/\text{s}^2$). The device only monitors and advises on the acceleration phase of driving as that corresponds directly to fuel consumption, but from the histogram it can be seen that there was also a reduction in the overall deceleration values. This is assumed to be due to the drivers being calmer and less harsh in their driving style. There are more data points for the cruising phase which adds to the hypothesis that drivers were smoother and did not have consecutive harsh throttle and brake usage.

To understand if the device had an effect on throttle usage, a measure called Pedal busyness was calculated. Pedal Busyness is a factor defined by Brace *et al.* [11] as the cumulative sum of the rate of change of throttle position over a complete cycle. The actual value has little significance, but it gives an idea of oscillatory behaviour in throttle pedal activation by drivers of the vans tested. For calculation of pedal busyness, a cycle or a time period has to be defined. It was

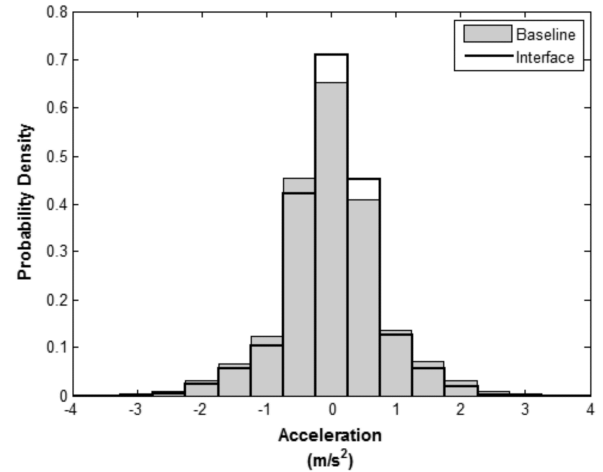


Figure 4. Acceleration and deceleration histogram for the tested vans

decided to delete idling instances that were longer than 90 seconds (as mentioned previously) and also divide the remaining data into segments of one hour. This would make comparing absolute values of pedal busyness possible. The difference in pedal usage between the baseline and interface trials was evident, as pedal busyness was lower for interface trials. Figure 5 shows the cumulative probability for pedal busyness for baseline and interface trials for all the vans. Pedal busyness does not start from zero as all idling data was deleted. It can be seen that during interface trials the pedal usage is less when compared to baseline tests. The curve suggests that the drivers were smoother in their driving style during interface trials when they were given real time audible feedback on their driving style. The increase in cruising period in the acceleration histogram together with the cumulative probability of pedal busyness being shifted to the left during the interface trial, suggests that the device had significant impact on not only their acceleration and inertial power surrogate, but also their pedal usage which shows that a direct link exists between the use of the device and driver behaviour.

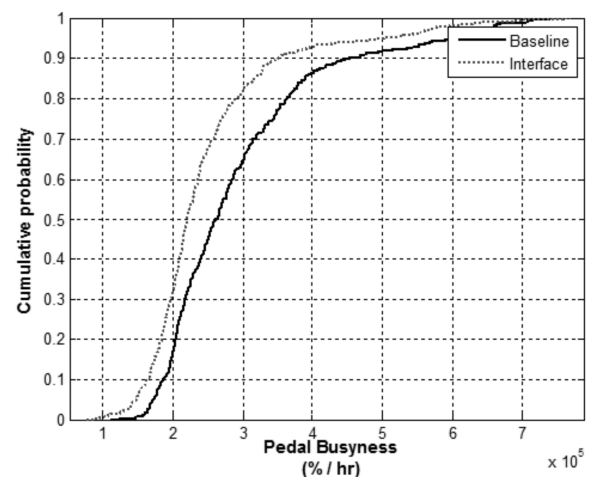


Figure 5. Cumulative probability for pedal busyness

Another factor considered in the analysis was specific work done, which is the work done by the vehicle per kilometer of distance travelled. This was calculated based on the drive cycle data of each vehicle. It is an indication of the tractive effort supplied by the engine of the vehicle when mass and all other factors are kept identical. On average over the entire fleet of tested vehicles, there was a 6.5% reduction in the energy used per kilometer for the interface trial. Even the vans that showed minimal improvement in fuel consumption exhibited a decrease in the specific work done. The fact that this decrease did not result in a larger reduction in fuel use suggests that they were either loaded differently during their interface trials or that they operated over a different drive cycle when compared to their respective baseline trials.

B. Predicting the fuel consumption benefit

Various parameters from the vehicle were analysed to identify which factors influenced the reduction in fuel consumption. The engine speed and IPS reduction from the baseline to interface trials had greatest correlation with the reduction in fuel consumption. It was observed that vans that had the greatest reduction in time spent at high values of IPS had the highest fuel consumption benefit. In an actual environment to witness a clear change in the above mentioned parameters, various factors have to remain unchanged between the two stages of comparison. Vans 9, 11 and 12 had to be omitted from the following plots as the operating conditions seemed to have changed between their baseline and interface trials. Even though Van 9 had comparatively good fuel consumption savings, it had been operating at a higher average speed during its interface trial, suggesting that it was involved in a lot more highway driving. The vehicle speed profile of the interface trial when compared to the baseline trial confirmed this. Vans 11 and 12 (belonging to the same company) seemed to have operated with a higher payload during the interface trial or in a drive cycle that was more demanding from the engine when compared to their baseline trials, since their energy per kilometer had risen during the interface trials.

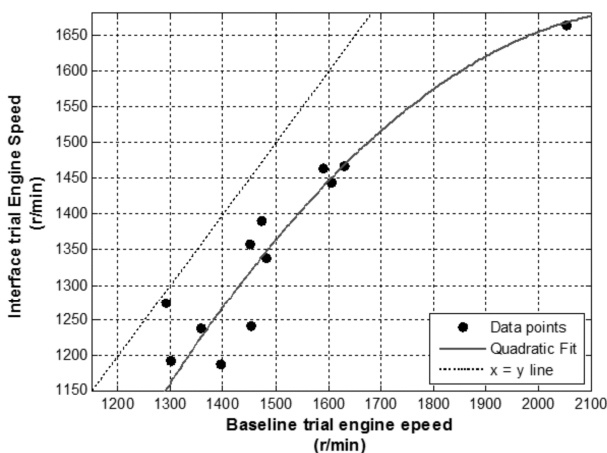


Figure 6. Quadratic fit showing average values of engine speed being reduced with the use of the device

Figure 6 shows the engine speed reduction with the use of the device (with the same vans excluded). The data points correspond to the vans considered in the analysis. The x-axis denotes the average engine speed during the baseline trial period while the y-axis denotes the same during the interface trial. A quadratic fit best represents the operation of the device in reducing the average engine speeds. This can be explained with the fact that drivers who had a high number of warnings during their baseline trials had most room for improvement. Thus the curve would plateau at medium to high values of baseline engine speed before starting to come back down. The quadratic fit has an R^2 value of 0.9139. The curve is relatively close to the $x=y$ line at low engine speeds and then diverges progressively, showing that vans with higher engine speeds during their baseline phase improved more compared to those having lower engine speeds.

Figure 7 shows the reduction in average IPS for the vans over the entire trial period. A fit with an R^2 value of 0.9194 was obtained for the plot. IPS is linked to two factors, the vehicle speed and acceleration. Reduction in acceleration has direct correlation to the tractive effort of the vehicle. Average vehicle speed mainly depends on the drive cycle.

After analysis of various factors that influence the driver behaviour, it was decided to create a model that would predict the savings in fuel consumption. The aim was to predict the fuel consumption benefit a vehicle would achieve based on its baseline average vehicle speed and IPS value. Average vehicle speed was chosen as an input to understand the drive cycle the vehicle mainly operates in. The model based calibration toolbox in Matlab was chosen for the model creation. A single stage model was used, having two inputs (baseline average speed and IPS) and one output (percentage of fuel saved).

Figure 8 shows the quadratic surface of the model generated to show the predicted fuel savings with the use of the device. The x-axis represents the average vehicle speed while the y-axis shows the average IPS value. It can be seen that fuel savings are higher at higher values of IPS and low to medium average vehicle speeds. This reinforces the fact that the device works best in urban driving conditions when the driver may demand more aggressive accelerations when unconstrained.

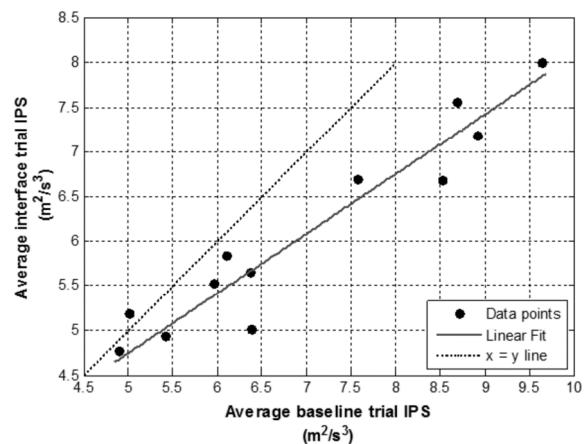


Figure 7. Linear fit showing average IPS values being reduced with the use of the device

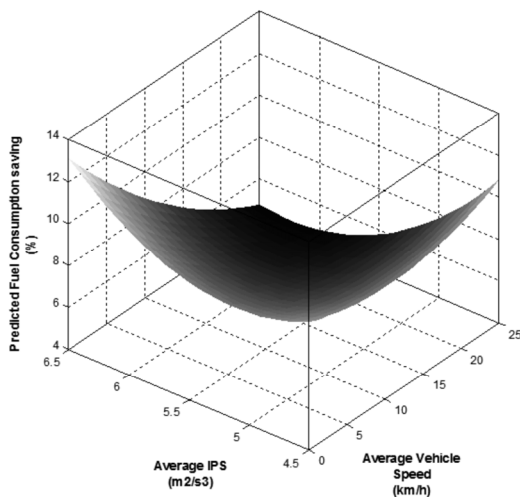


Figure 8. Predicted fuel savings with the use of the device

The model predicts that as expected there is maximum room for improvement for aggressive drivers in an urban driving environment. There is minimum improvement when the vehicle operates at high average speeds and high values of IPS, as vehicle speed is a significant contributor to the absolute IPS value. So if the drive cycle involves more highway driving, the improvements will not be as good those observed in an urban environment. But since the device is aimed at decreasing driver aggressiveness, some savings in fuel consumption can always be expected. According to the model, in most other cases, the vehicle would achieve moderate savings.

VI. CONCLUSION

An algorithm for a driver support tool has been designed for a device that provides real-time feedback to the driver to improve his driving behaviour. Trials were conducted on 15 light commercial vehicles for 4 weeks (two weeks of baseline and two weeks of interface trials). The data from the trials was analysed and it was seen that the device saved on average 7.6% of fuel, with the highest being 12%. This figure is reliable as the drivers were unaware of the system observing and collecting data on their innate driving style during the baseline tests. From further analysis it was observed that the device helps in saving fuel by not only reducing the IPS, but also by reducing the pedal busyness, which helps understand that the device actually modifies the driver's behaviour. The current version of the system is flexible enough to be fitted on to any car or van.

The model created from the data can be used to predict the savings that a vehicle would obtain once the device was fitted to it. The predicted savings would depend on the average vehicle speed and IPS.

Currently the device is being tested to identify a reduction in wear and tear of the vehicle due to reduced aggressiveness of the driver. For companies, this approach could help in reducing

the fleet fuel consumption, wear and tear and rate of accidents (due to less harsh or aggressive driving). If the device is fitted on most of the light commercial vehicles, it would help in significantly reducing CO₂ emissions, helping governments achieve their respective CO₂ emissions reduction targets.

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