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OPTIMIZATION ON VEHICLE FUEL CONSUMPTION IN A HIGWAY BUS USING VEHICLE SIMULATION

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ABSTRACT−This paper presents a numerical approach to optimizing vehicle fuel economy in a higway bus. The method described is based on using a commercial software vehicle simulation to identify the relative efficiency of each of the vehicle systems, such as the engine hardware, engine software calibration, transmission, cooling system and ancillary drives. The simulation-based approach offers a detailed understanding of which vehicle systems are underperforming and by how much the vehicle fuel economy can be improved if those systems are brought up to best-in-class performance. In this way, the optimum vehicle fuel economy can be provided to the vehicle customer. A further benefit is that the simulation requires only a minimum number of vehicle testing for initial validation, with all subsequent field test cycles performed in software, thereby reducing development time and cost for the manufacturer.

KEY WORDS : Vehicle simulation, Commercial vehicle, Engine calibration, Fuel economy, Optimisation

1. INTRODUCTION

Recently as the oil prices rise, as the fuel economy is more important than before. Particularly in commercial vehicle, the fuel price is directly reflected on the profitability of fleet owners' operational costs, to make ends meet a vehicle business. Therefore, it is strongly required for a commercial vehicle to get better fuel economy. This is a major factor for the profitability of a commercial vehicle for the customer and therefore there is a great pressure on manufacturers to provide the customer with the best possible fuel economy. This paper describes an approach to optimizing fuel economy for driving conditions in the real world using a combination of hardware testing and vehicle simulation (Heath and Mo, 1996; Berry and Blisset, 2002; Nasser *et al.*, 1998). A simulation model is first constructed and then validated against a small set of vehicle test data. Once the simulation model has been validated (Berard *et al.*, 2000; Whelan, 2004), there is no need for further, time-consuming and costly vehicle testing. All subsequent 'testing' of the vehicle can be performed in simulation – anything from driving on the open highway to rush- hour, stop-start congested traffic. The next stage of the approach is to use the simulation model to identify the relative contribution of each area of the vehicle to the overall fuel economy (Lyu and Kang, 2001).

For example, the significance of the following would be considered: engine base calibration, engine transient calibration, transmission ratio, vehicle aerodynamics and tire rolling resistance (Giannelli, 2005). The efficiency of the above areas can then be compared to best-in-class competitor vehicles to identify where improvements are necessary. It is also possible to calculate by how much the vehicle fuel economy would be improved if the each of the above areas were brought up to best-in-class. Knowing the relative sensitivity of fuel economy to each of these areas then allows the engineer to identify where the vehicle development programme should be focused to make the biggest fuel economy improvements (Cho, 2005; Hnatczuk and Laswcki, 2000). This approach therefore ensures that the optimum vehicle fuel economy is delivered to the customer. In this way, further savings in development cost and time savings are possible as the usually finite engineering resource is utilized in the most efficient way possible. The manuscript elements have been formatted for you through the "styles" capability of the software.

2. VEHICLE SIMULATION

A vehicle simulation model is a software-based representation of the whole vehicle and powertrain. The model can be made to follow a drive cycle, such as that of a typical customer, and the fuel consumption of the vehicle calculated. Performance parameters such as top gear

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acceleration or acceleration through the gearbox can also be calculated. The effect on fuel consumption and vehicle performance made by changing vehicle hardware or even engine software can then calculated over the same customer drive cycle. For example, the final drive ratio can be changed or the engine injection timing map modified, both taking just a few seconds to change in the simulation model and a few hours to calculate. Engineering time was signifiantly reduced compared to the long time it would take to make such changes to a real vehicle and then field test it. In this way, many different development options (hardware and software) can be investigated, not only in a very short time and resource efficient manner, but also under repeatable drive cycle conditions.

Under real field trial conditions with commercial vehicles there is often very significant variability in fuel consumption measurement results due to traffic conditions, different test drivers and even weather conditions such as wind direction and ambient temperature. These variations make it very difficult to measure the true effect of hardware changes and often lead the development engineer to make a number of repeat field trials, again taking up more time and engineering resources. The vehicle simulation model is not susceptible to this variability, and thus a single simulation run will provide the true fuel consumption result. Even very small changes in fuel consumption, e.g. 0.25% will be detected reliably. With real field trials such small percentages are lost in the measurement variation. A further advantage to be gained from the repeatability of the vehicle simulation is that it becomes possible to compare different vehicles, for example a competitor vehicle or a future prototype vehicle, under exactly the same field trial conditions (same driver, same traffic, same payload, etc).

2.1. Simulation Method

A commercial software (V-SIM) stands for Vehicle Simulation and is the name of the software developed by Ricardo that has been used in this study. These vehicle models are made up of a number of sub-system models that are 'plugged' together to form the overall vehicle simulation model A number of sub-system models, including driver, engine, clutch, transmission and rolling chassis were used in this commercial vehicle study (see Figure 1).

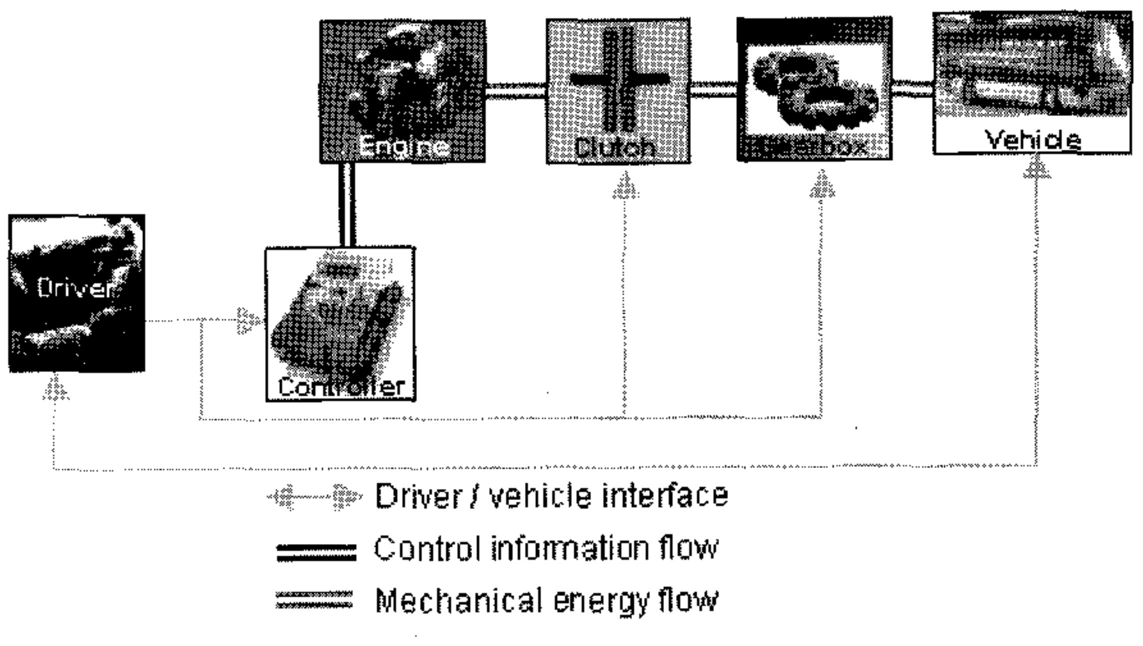

Figure 1. Commercial vehicle model.

However, the simulation could be extended to explore future developments by adding further sub-system models from an existing library. The Ricardo simulation library (V-SIM) contains detailed models of all vehicle systems from engines to transmissions, electrical systems, vehicle platforms, controllers, and Emissions Control Technology (ECT). It allows the construction of vehicle models of various complexity levels to be constructed, and ultimately provides accurate predictions of vehicle fuel consumption, emissions and performance over any drive cycle or indeed any road condition. A subset of the V-SIM library is the ECT models. ECT models predict emissions and temperatures within an exhaust system containing emissions catalytic devices, and are also used to assess regeneration strategies. These models, coded in MATLAB/Simulink®, follow standardised input and output conventions which offer complete model modularity ('plug and play'). The range of model applications is very wide and includes rapid concept assessment and performance prediction, definition of a fully integrated and optimised solution, and high-level control strategy simulation.

2.2. Validation of the Simulation Model

The vehicle model must be validated to real vehicle test measurement data before it can be used for such a study. In this case, measurements were made on the vehicle during a field trial. Measurements of were logged on a second by second basis, with the following being the main measurements necessary for validation:

- vehicle speed
- engine speed
- fuel flow
- accelerator pedal actuation

The simulation model was then run over the same field

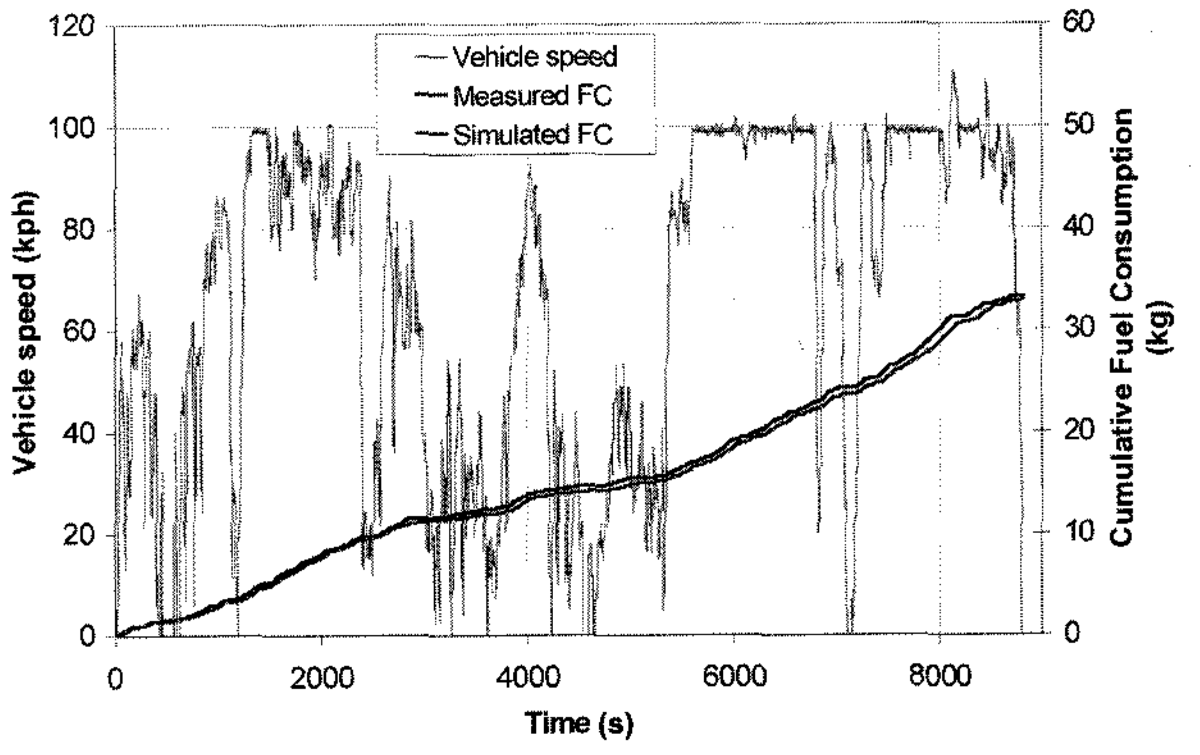

Figure 2. Model validation.

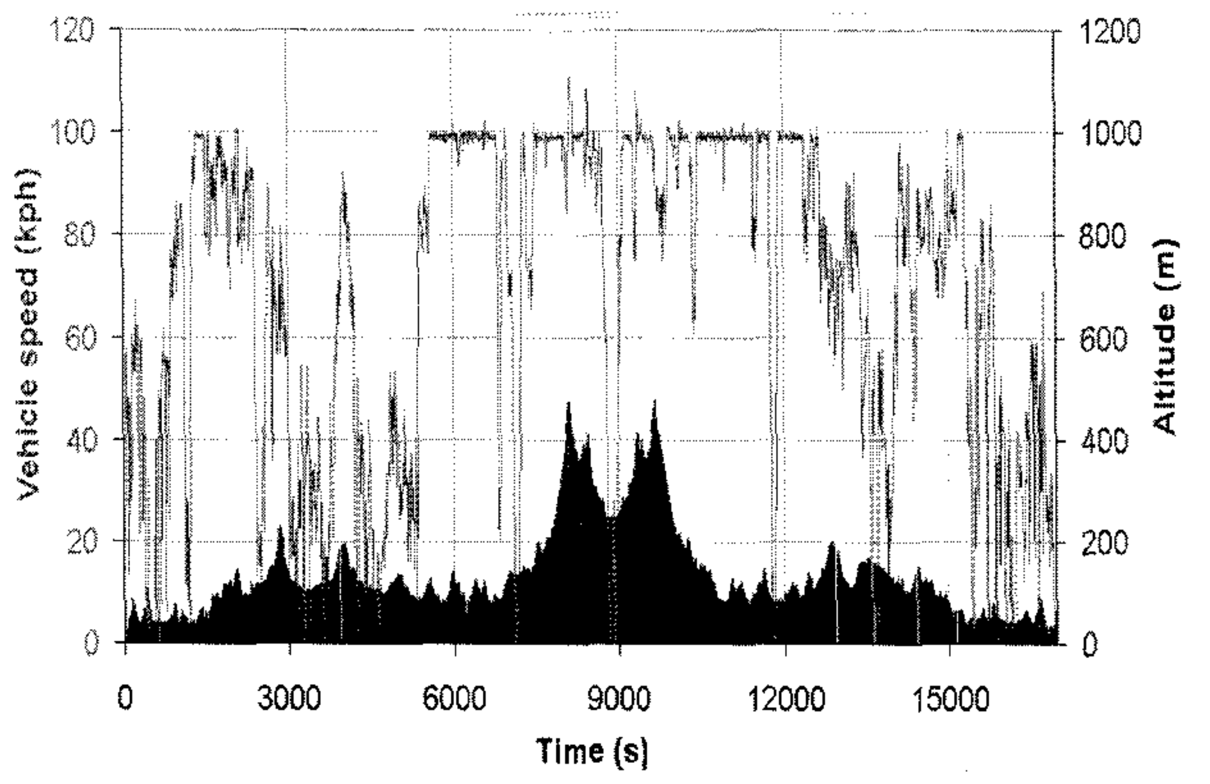

Figure 3. Customer drive cycle data.

trial cycle and, in this case, the fuel flow predicted. Close correlation between measured and predicted fuel consumption was found as shown in Figure 2.

2.3. Customer Real Drvive Cycle Data

The drive cycle that the V-SIM model is run over is usually derived from real measured data, such as a vehicle field test or from customer vehicle logs. However, it is also possible to use V-SIM to predict over legislated cycles such as the EUDC. Gathering real world drive data is often the most useful for this type of study where reduction of customer fuel consumption is the goal. In addition, the measured data may also be used to developed durability test cycles and so can be shared with other areas in the OEM's organization

2.3.1. Drive cycle data drom a single source

A drive cycle can be obtained, as described above, from a single field test of a vehicle over a single drive route in Figure 3. This approach is used where the drive routes of the vehicle are well known and are relatively similar from customer to customer. An example of this might be a highway bus where most customers will drive routes starting in town, spending the majority of the time on the highway and then finishing in a town. Bus vehicle drivers also tend to have similar driving styles relative to the range of driving styles that can be found in, for example, a passenger car application. This approach is the most straightforward, analytically, and requires the least vehicle measurement data.

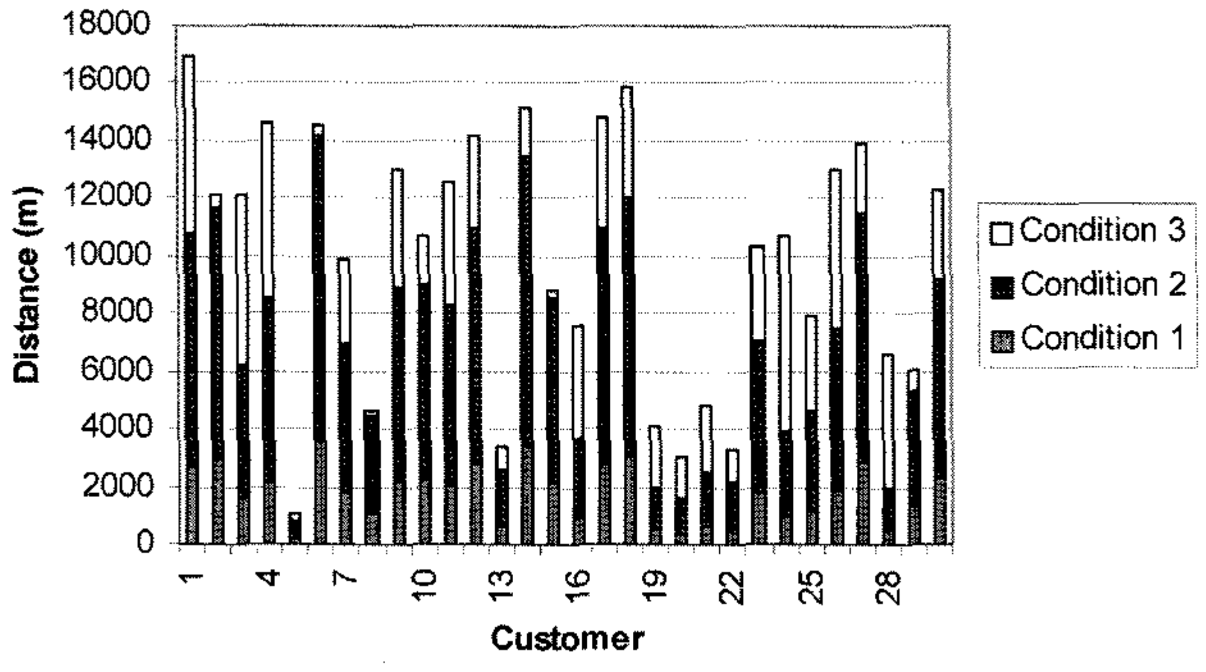

Figure 4. Vehicle data logs for 30 customers.

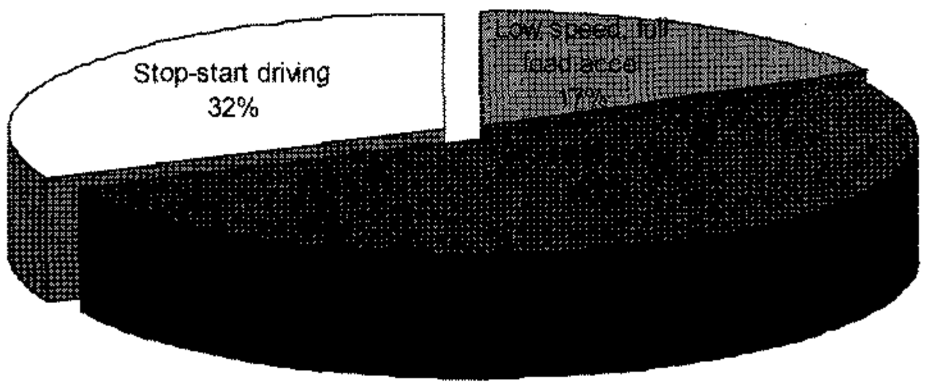

Figure 5. 95th percentile customer drive cycle.

2.3.2. Drive cycle data from multiple sources

In situations where the vehicle might be used on a number of different types of drive routes and by many different types of driver, it is preferred to use a drive cycle that has been statistically compiled from measurements of a number of customer vehicle data logs, as shown in Figure 4 and 5.

3. IDENTIFYING FUEL CONSUMPTION CRITICAL COMPONENTS

Once the V-SIM model has been constructed, validated and given the approprtiate drive cycle data, it is used to identify the vehicle components that are critical to fuel consumption

3.1. Breakdown of Vehicle Components

The first step is to break the vehicle down into its various components, such as engine, transmission, tires, etc. Fortunately, the modular construction of V-SIM, with its many sub-system models, naturally lends itself to being broken down into separate components. The fuel energy flowing into each component can then be calculated and the relative significance to fuel consumption identified, as shown in Figure 6.

3.2. Benchmarking of Components

Knowing the fuel energy input to each of the components

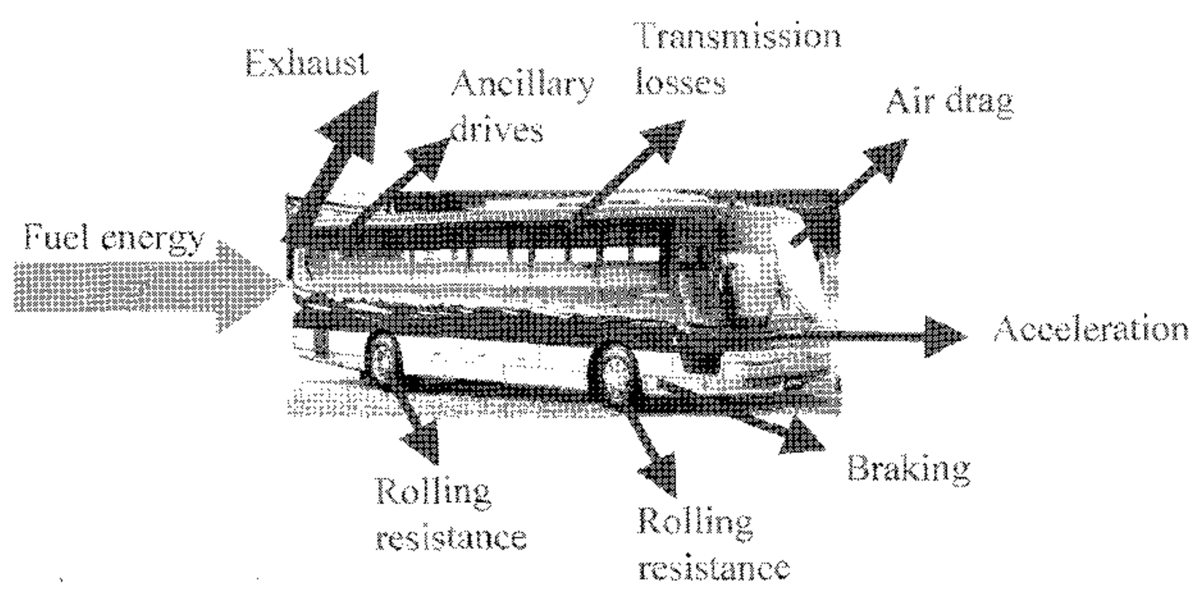

Figure 6. Diagram of fuel energy flows.

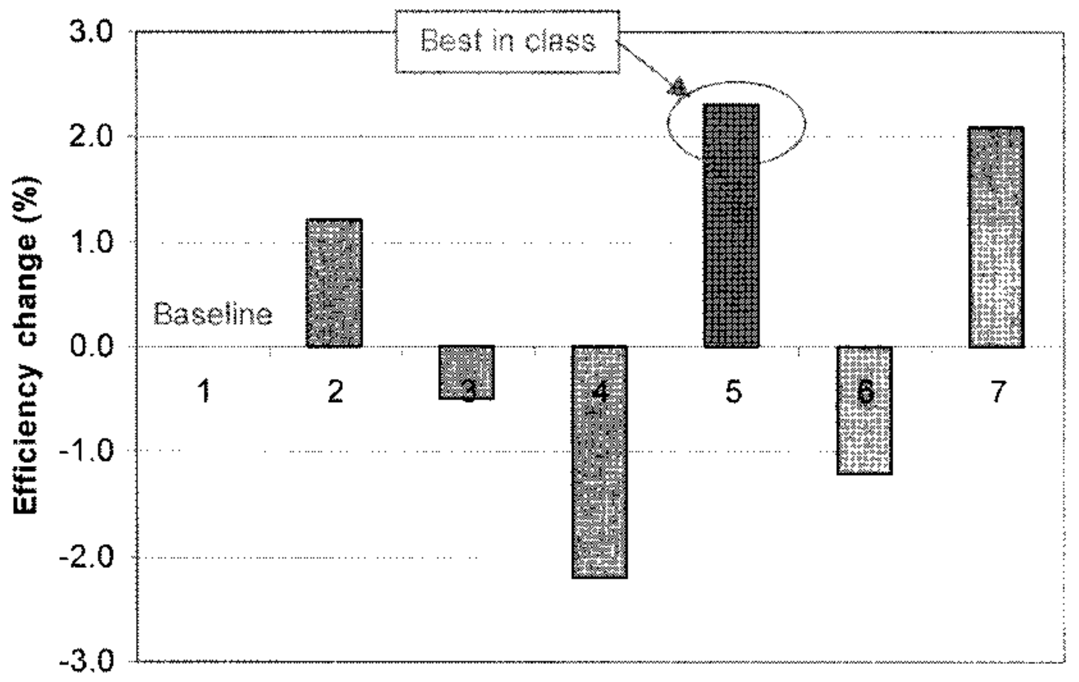

Figure 7. Efficiency comparison to best in class.

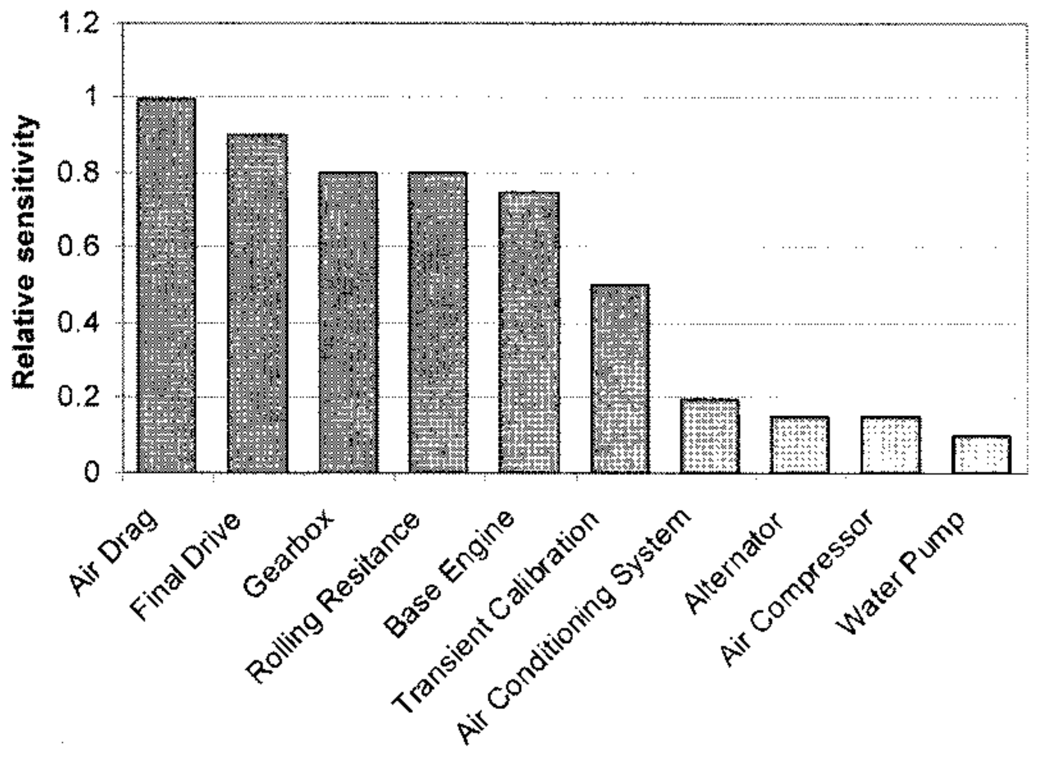

Figure 8. Fuel consumption sensitivity ranking.

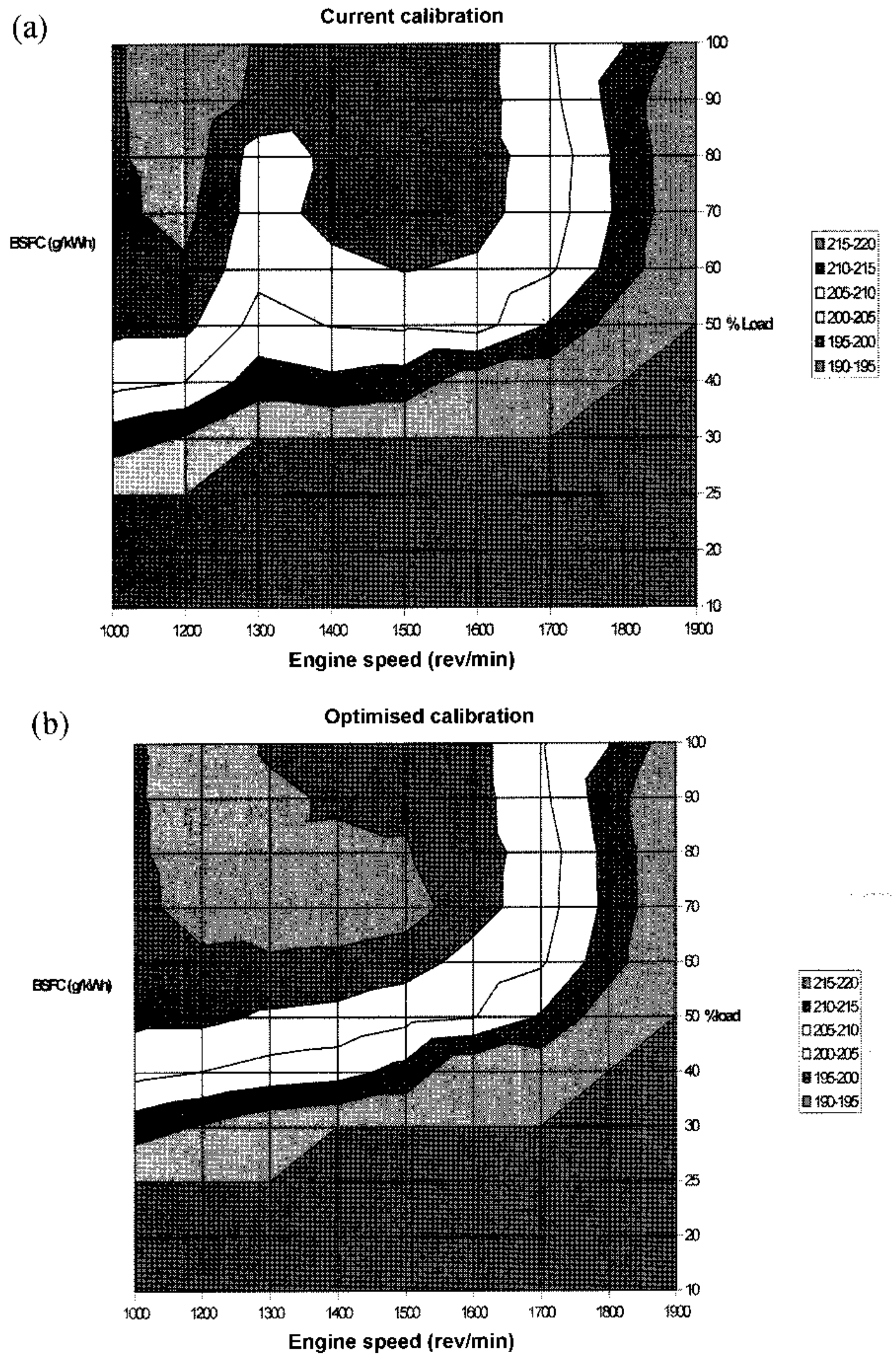

Figure 9. (a) Current engine calibration map. (b) Optomized engine calibration map.

and the useful workout, it is possible to calculate the component efficiencies. These efficiencies can then be compared to alternative components, maybe from different suppliers, and therefore establish if the current component is the best in class or otherwise (Figure 7). Where a component might be low on efficiency, it is also possible with V-SIM to replace just that sub-system model with the best-in-class component and calculate the improvement in fuel consumption over the drive cycle.

3.3. Sensitivity Study

A parametric study of each component can be undertaken to assess the relative sensitivity of vehicle fuel consumption. For example, a 1% improvement in transmission efficiency may lead to a 1% improvement in vehicle fuel consumption whereas a 1% improvement in the efficiency of the air conditioning compressor may only improve vehicle efficiency by 0.25%. Calculating the sensitivity for each component then allows the components to be ranked in sensitivity order in Figure 8, naturally identifying the areas where improvement would have the most effect. This is also a powerful way of also identifying the components on which engineering development resource should be focused to maximize the benefit to vehicle fuel economy.

4. CASE STUDY EXAMPLES

4.1. Engine Calibration Map Optimisation

Engine calibration mapping changed to optimize fuel consumption for the vehicle drive cycle in Figure 9. Key engine operating areas are identified from V-SIM analysis of the customer drive cycle data. The engine calibration maps are then optimized to improve BSFC in these areas while still maintaining emissions below legislated cycle limits.

4.2. Transmission Ratio Optimisation

A matrix of 13 different vehicle transmission and engine rating configurations were investigated using V-SIM over the customer drive cycle in Table 1.

Fuel consumption changes were calculated and presented in terms of the percentage change allowing easy identification of the most fuel economical build configuration (see Figure 10). Vehicle performance is also predicted, in this case the top gear acceleration between

Table 1. Tabulated results for different powertrain and vehicle conditions.

Build	1	2	3	4	5	6	7	8	9	10	11	12	13
Base engine calibration	×	×	×				×	×	×	×			
Uprated engine calibration				×	×	×					×	×	×
Std 5 speed transmission				×			×		×				
Revised 5spd transmission		×			×							×	
6 speed transmission			×			×		×		×			×
Gearbox efficiency = 100%	×	×	×	×	×	×							
Gearbox efficiency = 93%							×		×		×	×	
Gearbox efficiency = 98%								×		×			×
Vehicle weight = 14700 kg	×	×	×	×	×	×	×	×			×	×	×
Vehicle weight = 14480 kg									×	×			
Upshift speed = 1700 rev/min	×	×	×	×	×	×	×	×	×	×	×	×	×
Downshift speed = 900 rev/min	×	×	×	×	×	×	×	×	×	×	×	×	×
Fuel Consumption (kg)	65.9	65.4	65.1	66.0	65.6	65.2	69.7	66.1	69.3	65.7	69.8	69.4	66.2
0-80 kph (s)	22.4	21.9	21.8	21.4	20.9	20.8							
80-100 kph in top gear (s)	12.7	13.5	13.0	11.9	12.6	12.2							

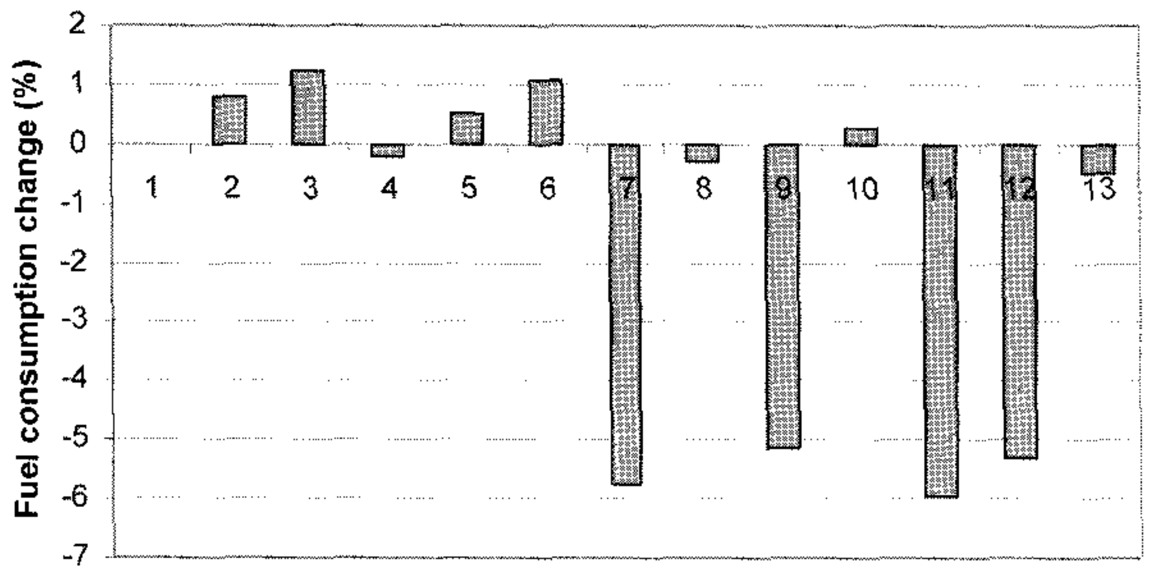

Figure 10. Plotted results for fuel consumption changes.

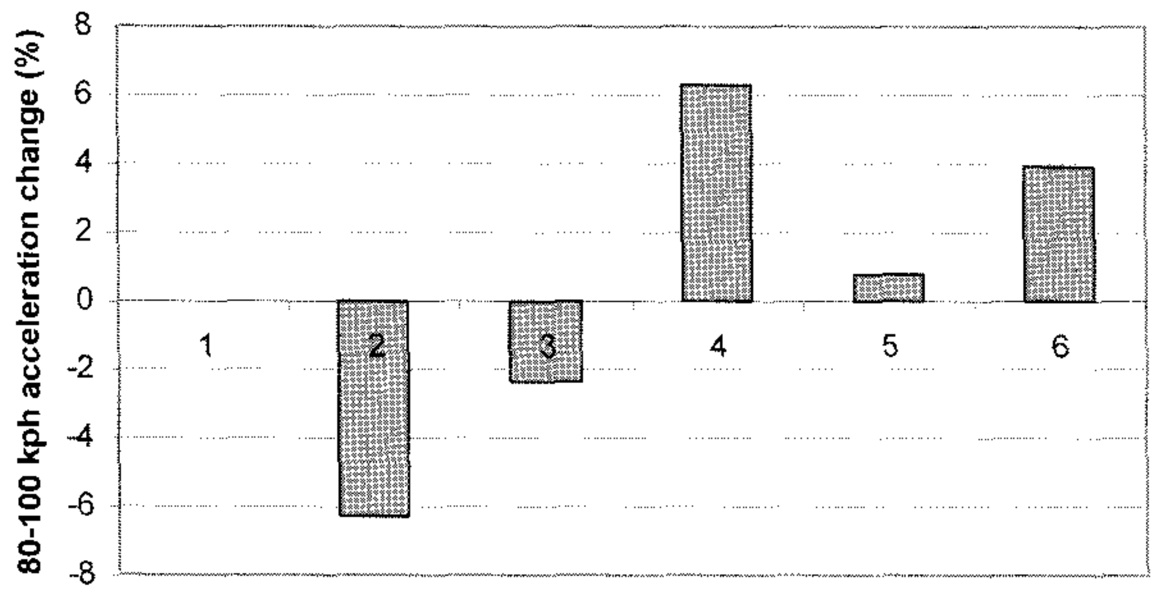

Figure 11. Plotted results for vehicle performances.

80 and 100 kph. Again, it is easy to identify the effect each build configuration has on acceleration (see Figure 11). These analyses are then used to choose the build configuration that provides optimum fuel economy while still maintaining vehicle performance at an acceptable level.

5. CONCLUSIONS

A vehicle simulation approach to the optimization of vehicle fuel economy has been shown to have several advantages over the traditional testing-based approach.

The vehicle simulation;

(1) reduces the amount of time-consuming and expensive vehicle testing, thereby compressing development schedules

(2) provides detailed information about the vehicle sub-system efficiencies

(3) enables fuel consumption sensitivity ranking of the vehicle sub-system components permitting better focus of limited development engineering resources on the components that will give maximum improvement in fuel consumption.

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