

Powertrain Architecture Affects Driving Habits

Harald Stoffels and Kay Hohenboeken
Ford Werke GmbH

ABSTRACT

The impact of the number of cylinders on two downsized gasoline engines on driving habits in the same passenger-vehicle type was investigated. This was carried out with two similar vehicles, equipped with an in-line three cylinder (i3) and an in-line four cylinder (i4) engine, both having same power, torque and transient-response behaviour. Both engine types were mated to six-speed manual transmissions with same gear-ratios and dual-mass flywheel characteristics. The study was performed by letting a statistically significant number of subjects driving the same route and both vehicles consecutively. The relevant data during driving were recorded simultaneously from either vehicle integrated sensors (CAN), and secondary transducers.

We found that the in-line three cylinder was operated at higher engine speeds even though it was operated at similar acceleration- and load levels like the in-line four cylinder power-train, whereat the off-set of the engine speed shows no correlation with the difference in firing frequency between both engine types. Furthermore, it was revealed that the i3-engine faced gear-up-shift events at higher engine speeds than the i4-engine. Interestingly, the up-shift speeds in the individual gears show good correlation with the individual interior noise level characteristics. Based on the findings, potential countermeasures to enforce drivers of in-line three cylinders to drive at lower engine speeds can be made to ensure that the fuel-economy benefit of i3-engines is accessible even under real-world driving conditions.

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INTRODUCTION

In order to reduce fuel consumption, downsizing has been revealed as an affordable and efficient path. This can result in a reduced number of cylinders in internal combustion engines. Moreover, a unification of engine systems is in the focus of development. This can result in i3-architectures with a power and torque density formerly covered by i4-engines. But, in certain displacement classes this picture can be ambiguous, as for example the displacement below $V_h < 1.6 dm^3$ could be covered by either i3 or i4-engine-architectures. However, the noise and vibration characteristics of i3-engines are different to i4-engines [1,2,3] with the risk, that if the firing order f_e [7] of the individual engine architecture can affect the engine operation and driving habits of the customer, finally letting the customer revving an i3-engine at higher engine speeds than a comparable i4-engine. In turn, this would mean that potential benefits in fuel consumption associated to i3-engines versus i4-engines are bearing the risk of getting over-compensated, as there might be the case that the driver tries to compensate the lower firing frequency of the i3-engine to an i4-engine while revving the i3-engine higher to achieve i4-engine frequencies. A general theory in the room is that the normal customer drives

the engine based on the perception of the firing frequency as a potential dominating contributor to the overall vehicle interior noise characteristic. However, the firing frequency of i3-engines is rather perceived as a fluctuation below an engine speed around approximately $n_{Eng} = 1300 rpm$ or $f_e(1.5^{th} EO) = 33 Hz$ than as a kind of roughness [10,11], and therefore the question of the validity of this general theory for i3- versus i4-engines was identified to be proven. Subsequently, a study was initiated, governed by the question, whether i3 and i4-engines are operated similar under customer conditions or not.

SURVEY DESIGN

Conducting a survey successfully depends on robustness and control of the parameters affected and the management of potential noise-factors that can occur, especially when a study is performed on public roads as it was carried out in the study presented in this paper. The main contributors and their control are laid out in the following sub-sections.

The Drive-Cycle

Total length of the drive cycle on public roads was 52.5km, consisting of ~15% motorway, ~65% cross-country and ~20% intra-urban driving. Maximum speed allowed by traffic regulations was $v_x=130\text{km/h}$. The route was partly entering a low mountain range, comprising a maximum road gradient of appr. 15%, that was entered during driving. The route was driven consecutively by the subjects with both vehicles at similar times on working-days to keep the variation brought by the public traffic at a minimum.

Vehicle and Engine Set-Up

Two C-car vehicles were selected, having same specification and body style. Gear ratios of the manual six-speed transmission, flywheel, driveline and tyre specification were the same on both vehicles. The only difference was the engine architecture. However, both engine architectures, i3 and i4, were calibrated to $P=88\text{kW}$ power output and a maximum torque of $T=200\text{Nm}$. Special attention was given to the transient response of each engine architecture in the individual gears as this can affect driving habits significantly [8]. Without touching the pedal maps, same in both vehicles, the engines were calibrated to deliver equal transient torque response when demanded by the driver in all gears and engine speeds. The shift indicator light in both vehicles was disabled, so was the radio and entertainment system.

Basics of NVH-Characteristics of i3 and i4-Engines

The design for NVH of i3 and i4 engines in detail is already presented in the literature, for example basic details and effects can be drawn from [1, 2, 3]. One focus is on the amplitude of the individual firing order, namely the 1.5th on the i3, and the 2nd order on the i4-engine, and its dependency on engine load. A comparative analysis of both is depicted in Figure 1.

Whilst the amplitude of the i3-engine architecture is dominated by the torque-characteristics of the engine itself, the picture for the i4-architecture is different: caused by the i4-architecture, there is an engine speed, where gas-forces, occurring in the low-speed region, and mass-forces, rising progressively at higher engine speeds, are compensating each other. Moreover, this minimum moves to higher engine speeds, when the engine load is increased [3] with the gas-force excitation content growing into the main engine speed operation range.

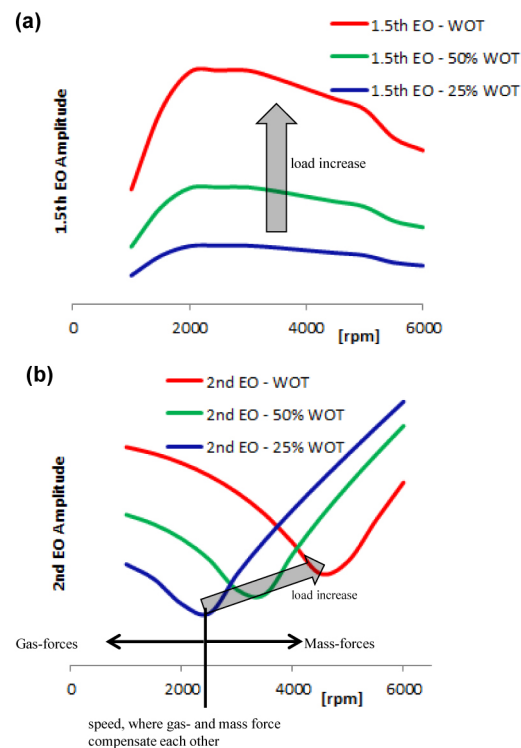


Figure 1. Amplitude versus engine speed and load-dependency of engine firing order of (a) i3-, and (b) i4-engines.

Selection of Subjects

The number of subjects required for the study was calculated using the two-sample *t-test* approach [13], considering the engine speed range of the two powertrains used in this study, and reflecting an expected difference in engine speed operation, processed from a comparison of the firing frequencies, of the two engine architectures. Aim was to reach a significance level of 95%, resulting in a minimum of 21 subjects required. The group of subjects was finally consisting of 35% female and 65% male participants. A pre-requisite for the selection of subjects was that they are not experts in any discipline of powertrain engineering or even NVH and other vehicle attributes. All subjects had to answer a pre- and a post-drive query, for example identifying any hearing losses or special habits when driving their private car. Of certain importance is the private vehicle that is operated by the subject mostly: 90% of all subjects are driving vehicles equipped with manual transmissions, and also 90% of all subjects are driving vehicles equipped with either i3- or i4-engines; 28% of all subjects are driving vehicles equipped with a Diesel engine.

After finishing driving the two vehicles, all subjects were asked about their usual driving- and gear-shift habits, and whether they attended for example Eco-driving courses in the past.

RESULTS AND DATA-ANALYSIS

The vehicle was equipped with transducers delivering the vehicle acceleration in all three translational directions nearby its centre of gravity, and one accelerometer suited at the head-rest of the driver's seat. Gear position, road-gradient, interior noise and vibrations at relevant comfort positions were recorded. In parallel, vehicle and powertrain parameters such as engine- and vehicle speed and pedal position and brake intensity were gathered from the vehicle CAN-bus. Furthermore, the roll-out curve parameters were processed for both vehicles, in turn enabling an estimation of the *bme_p* based on the vehicle acceleration signal. In order to better reflect the individual driving style of each subject, some figures in the following sub-sections will show vehicle related parameters versus distance driven for each individual subject in one graph. This should allow the reader e.g. to better detect any spikes or outliers, even though readability of the figure might be affected by this. However, it furthermore revealed better for the understanding of the consistency of each data set relative to each other, instead of showing a min-, max- and average data-set solely.

Vehicle Speed Analysis

Figure 2 shows the vehicle speed (sample rate 1kHz) for all subjects over the driven distance for both vehicles.

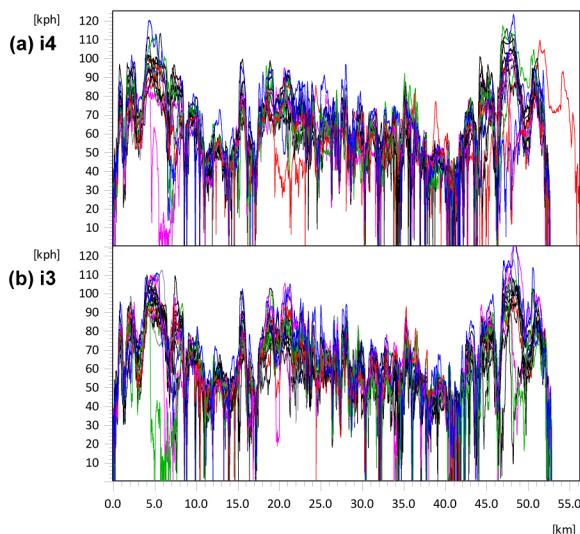


Figure 2. Vehicle speed versus driven distance for both vehicles: (a) i4-, and (b) i3-engines.

With some single exceptions (on i4 one subject took the wrong way, resulting in a longer distance travelled), and i3 and i4, where both subjects faced a traffic jam), one can state a very good conformity of the vehicle speed versus distance for all subjects, resulting in a statistical analysis as depicted in Figure 3.

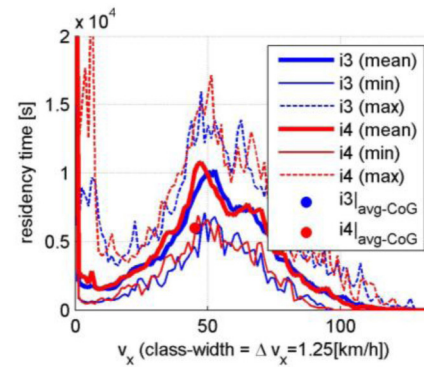


Figure 3. Comparative analysis of residence time of vehicle speed v_x for both vehicles

Processing the center of gravity (CoG) of the distribution of residence time in the individual vehicle speeds with a class width of $\Delta v_x = 1.25 \text{ km/h}$, the statistical analysis yields $v_x(i3)|_{\text{CoG}} = 45.93 \text{ km/h}$, $v_x(i4)|_{\text{CoG}} = 45.04 \text{ km/h}$, resulting in a difference between both vehicles of $\Delta v_x = 0.89 \text{ km/h}$. Thus, a very good conformity of vehicle speed for all test-runs can be stated.

Engine-Speed Analysis

However, even though the vehicle speeds revealed good conformity, it is obvious that each subject might achieve similar vehicle speeds in different gears, thus operating at different engine speeds. Figure 4 shows the engine speed (n_{Eng}) profiles for all subjects versus driven distance (sample rate 1kHz).

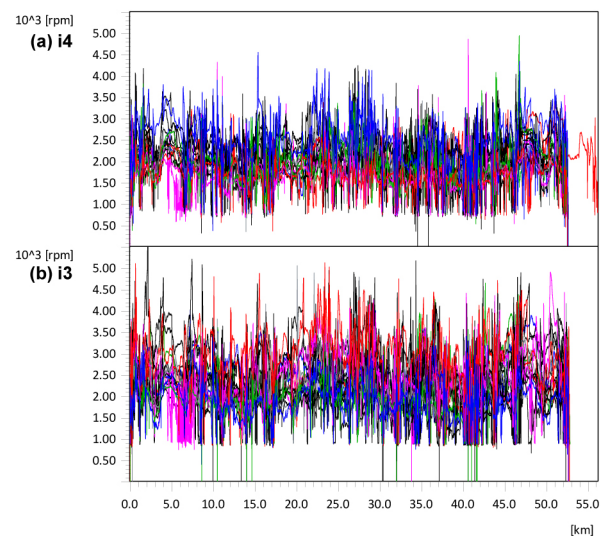


Figure 4. Engine speed versus driven distance for both vehicles: (a) i4-, and (b) i3-engines.

First differences can be seen in Figure 4, finding the i3-engine operated at a higher spread of engine speeds, resulting in the following results of a statistical analysis, depicted in Figure 5(a).