

Advanced Combustion System Analyses on a 125cc Motorcycle Engine

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ABSTRACT

Environmental consciousness and tightening emissions legislation push the market share of electronic fuel injection within a dynamically growing world wide small engines market. Similar to automotive engines during late 1980's, this opens up opportunities for original equipment manufacturers (OEM) and suppliers to jointly advance small engines performance in terms of fuel economy, emissions, and drivability.

In this context, advanced combustion system analyses from automotive engine testing have been applied to a typical production motorcycle small engine. The 125cc 4-stroke, 2-valve, air-cooled, single-cylinder engine with closed-loop lambda-controlled electronic port fuel injection was investigated in original series configuration on an engine dynamometer. The test cycle fuel consumption simulation provides reasonable best case fuel economy estimates based on stationary map fuel consumption measurements. For Indian Driving Cycle (IDC) it yielded roughly 1.4l/100km, for World Motorcycle Test Cycle (WMTC) 1.8l/100km. The thermodynamic split of losses analysis of test-cycle relevant operating points provides deeper physical insight into engine physics and reveals optimization potential. Namely, full load and low load enrichment increase fuel consumption, particularly at high engine temperatures. At colder engine, the ignition system is not capable to maintain an efficiency-optimal combustion phasing and the engine roughness increases. Such findings shall promote the development of customized single components and complete modular systems for 2-wheelers.

INTRODUCTION

The need for fossil fuel powered individual mobility is further increasing around the world. This trend is reflected by dynamically growing 2-wheeler sales volumes particularly in emerging markets, 95% of these vehicles being powered by small engines below 250cc. At the same time, the necessity to reduce pollutant emissions especially in urbanizing areas gives reason to further tighten emissions regulations. Along with global agreements to reduce carbon dioxide emissions, and increasing customer sensitivity to

ever-growing fuel prices, these boundary conditions push the market share of engine management systems (EMS) with closed-loop lambda controlled electronic fuel injection (EFI) and three-way catalytic exhaust gas after treatment.

Similar to automotive engine development during late 1980's, this development opens up a variety of additional technical opportunities for OEMs and suppliers in terms of fuel economy, emissions, and drivability. A thorough understanding of small engines combustion system physics is thereby inevitable to develop customized single components and complete modular systems. The first high end motorcycles were equipped with Bosch EMS in the late 1980's. This work focuses on applying automotive technical experience and advanced analysis methods to a globally more typical 2-wheeler small engine.

First, stationary engine map fuel consumption measurements were conducted on an engine dynamometer (dyno) at different engine temperatures. Second, fuel consumption test cycle simulations were performed to derive IDC and WMTC fuel economy estimates from the stationary map fuel consumption measurements. Third, the thermodynamic split of losses methodology was applied to derive fuel economy potential at test cycle relevant operating points.

EXPERIMENTAL ENGINE SETUP

Figure 1 (a) shows the 125cc 4-stroke, 2-valve, air-cooled single cylinder production motorcycle small engine under investigation. All measurements were conducted using its original series configuration. Other than measurement instrumentation, no changes have been made to hardware, software, or calibration.

The engine was connected to an automotive dyno (AVL Dyno Exact APA) via the gearbox output, i.e. after transmission. The gear had been selected to better match the speed operating and torque measurement ranges of the dyno. The engine was equipped with a variety of additional measurement systems, including engine out emissions exhaust gas analyzer (Horiba EXSA-1500), volume-based fuel consumption measurement system (AVL PLU which measures volume flow to calculate mass flow based on batch measured, and model-based temperature compensated

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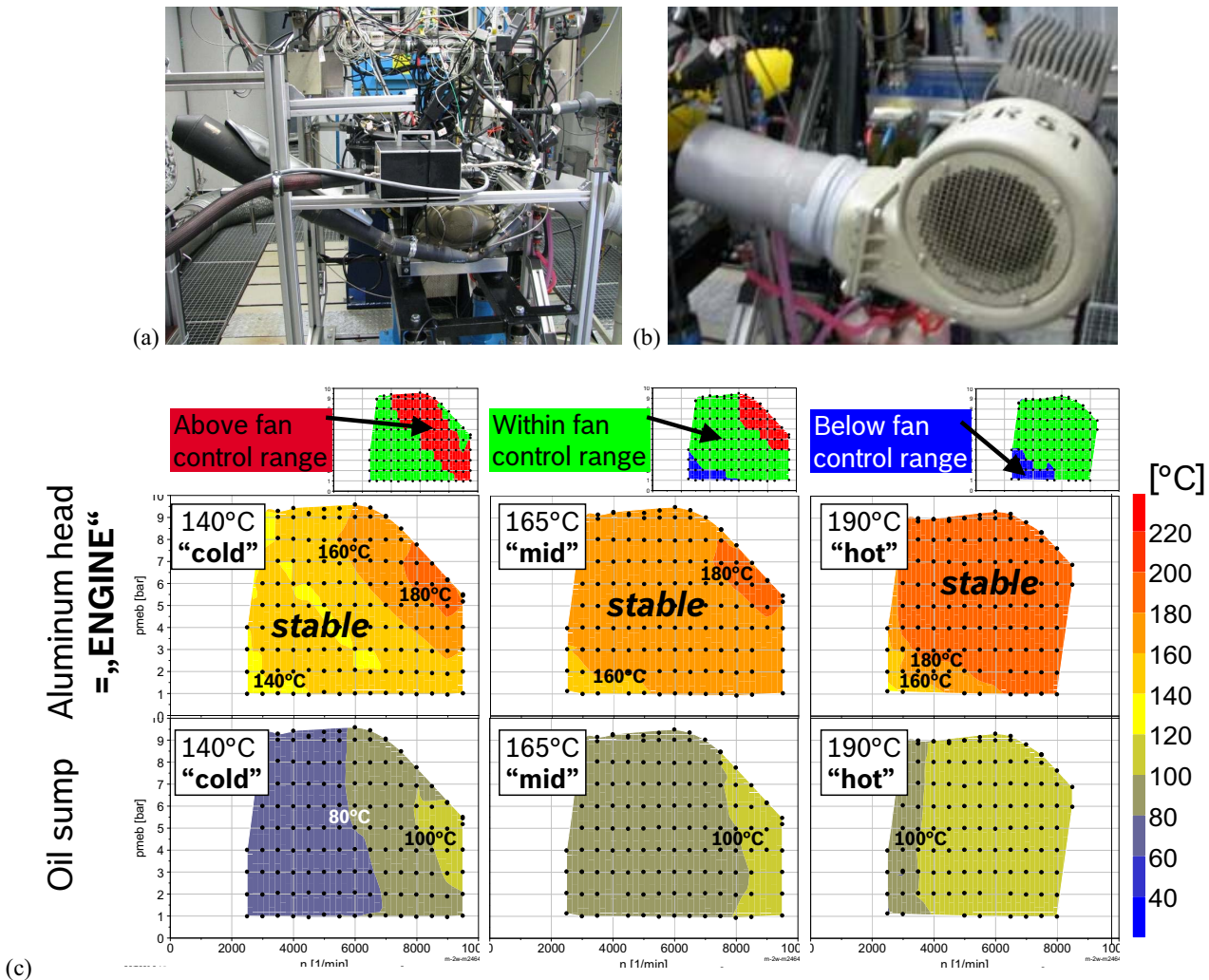


Figure 1. Engine and measurement systems setup in engine dyno test cell (a), controllably radial fan for external engine temperature control (b), three different, closed-loop controlled target temperature levels at engine head near spark plug seat (referred to as “engine temperature”) including fan control range boundaries and corresponding oil sump temperatures (c).

fuel density), and full pressure indication using intake, combustion chamber, and exhaust pressure sensors (Kistler), signals being recorded crank angle based with an indication system (AVL Indimaster, Indicom). An external speed sensor (Heidenhain) was mounted directly to the crank shaft in order to improve the crank angle resolution accuracy for pressure indication measurements to below 1cad, compared to the rough resolution of production EMS 12 minus 3 trigger wheel. Relevant injection and ignition signals are recorded with the indication system via a breakout box.

Temperature definition, monitoring, and control are not straight forward for air-cooled engines. Thermocouples are attached to numerous engine positions, e.g. oil sump and cylinder head near the spark plug seat (referred to as “engine temperature” in the following). Within the conditioned test cell environment, an external radial fan shown in figure 1 (b) provided an air stream with up to 100km/h air velocity directly to the cylinder head, allowing for stronger forced-convective cooling than at the specified maximum speed of the vehicle. The fan speed was closed-loop controlled to adjust different temperatures at the cylinder head.

Figure 1 (c) shows three distinct aluminum head target temperature levels 140, 165, and 190°C, covering the maximum achievable temperature range with the described control setup over the stationary engine map. The aluminum head temperature maps over engine speed and load indicate that the target temperature levels were stably maintained over the majority of the operating points. However, measured aluminum head temperatures significantly exceed the low level of 140°C at highest speeds and loads although the fan runs at full speed (i.e., approx. 100km/h fan air speed), and fall below the high level of 190°C at lowest engine speeds and loads even by means of natural convection, as the fan is completely shut off there (0km/h fan air speed). Valid control ranges are indicated in small plots above the aluminum head temperature maps. Figure 1 (c) also displays the corresponding oil sump temperatures, which are up to 80K colder than the aluminum head in stationary engine operation. Moreover, temperature gradients during transients are much slower in the oil sump than in the aluminum head. Engine temperature control via fan based on oil sump temperature was not possible, as the head would overheat before the fan turned on.

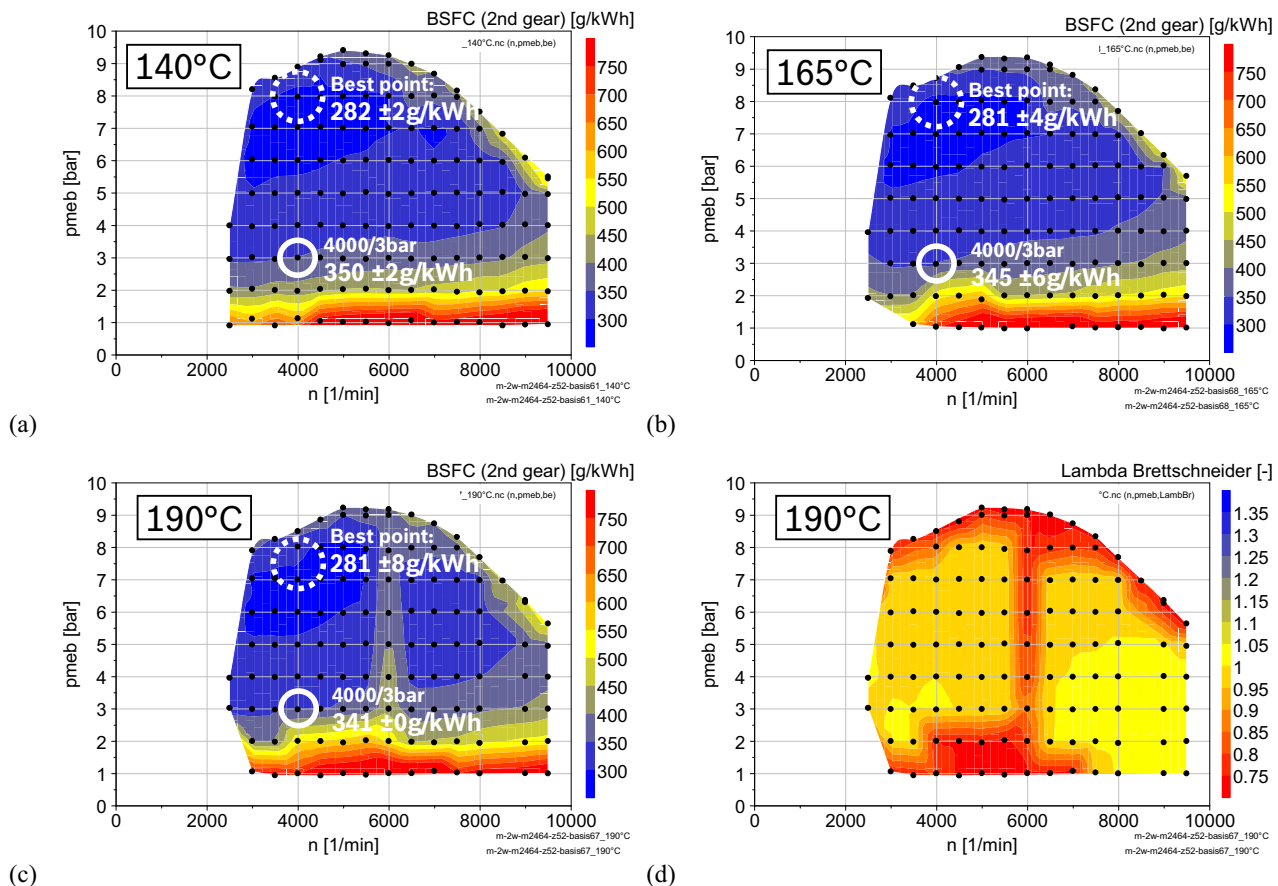


Figure 2. Brake specific fuel consumption (bsfc) from stationary engine map measurements at different engine (cylinder head target) temperatures: 140°C (a), 165°C (b), 190°C (c), including best point and 4000/3bar bsfc values, and air-fuel ratio at 190°C (lambda Brettscneider, d).

STATIONARY MAP RESULTS

Figures 2 (a)-(c) show the stationary brake specific fuel consumption (bsfc) maps over engine speed and load at three engine temperatures 140, 165, and 190°C. The measurements include mechanical friction of the transmission. The engine achieves its lowest specific fuel consumption of slightly above 280g/kWh close to lowest speeds and highest loads, virtually independent of engine temperature. At higher speeds mechanical friction increases, while at even lower speeds a lower charge motion reduces combustion quality. At highest loads the full load enrichment increases specific fuel consumption. Along with the absolute values, a variation range is given from repetitive measurements, indicating good measurement reproducibility. Besides the full load enrichment, the EMS original series calibration deviates from lambda-controlled stoichiometric to rich mixture at (low to mid speed) lowest loads. This effect increases with engine temperature: at 190°C enrichment occurs even at intermediate speeds and loads (see figure 2 d). While the purpose of enrichment close to idling is most likely an improvement of engine roughness, the purpose of enrichment at 6000/min mid loads is unclear. It does have a negative influence on the fuel consumption of the affected operating points at 190°C though. In general, the degree of enrichment down to below lambda 0.75 at full load and low loads is rather strong, also SETC2011

increasing the fuel consumption in a large fraction of the engine operating map. Figures 2 (a)-(c) also state the fuel consumption at the typical part load point of 4000/min, 3bar brake mean effective pressure (bmep), which is not influenced by enrichment. Fuel consumption there is almost constant in view of the measurement accuracy, with very light indication of higher fuel consumption at colder engine.

TEST CYCLE SIMULATION

The fuel consumption test cycle simulation (e.g. [1, 2]) has been applied to estimate the fuel consumption of the vehicle based on the stationary engine map dyno measurements presented above. Two different test cycles have been considered: IDC and WMTC. IDC is utilized in the current Indian Bharat Stage III legislation. As can be seen in figure 3 (a) it is an artificial cycle including only moderate vehicle speeds up to 42km/h and accelerations up to 2.3km/(hs). From shifting pattern and gear ratios, this yields only low engine speeds up to 4500/min. Using vehicle weight, friction, aerodynamic drag, and inertia, loads are calculated which do not exceed 3.5bar bmep. WMTC is likely to replace IDC for 2013 Indian Bharat Stage IV, and is also becoming mandatory in most other regions of the world including Europe. Compared to the IDC, it is including significantly higher vehicle speeds up to 85km/h and accelerations up to 10km/(hs) in a rather unsteady, see Figure 3 (b).

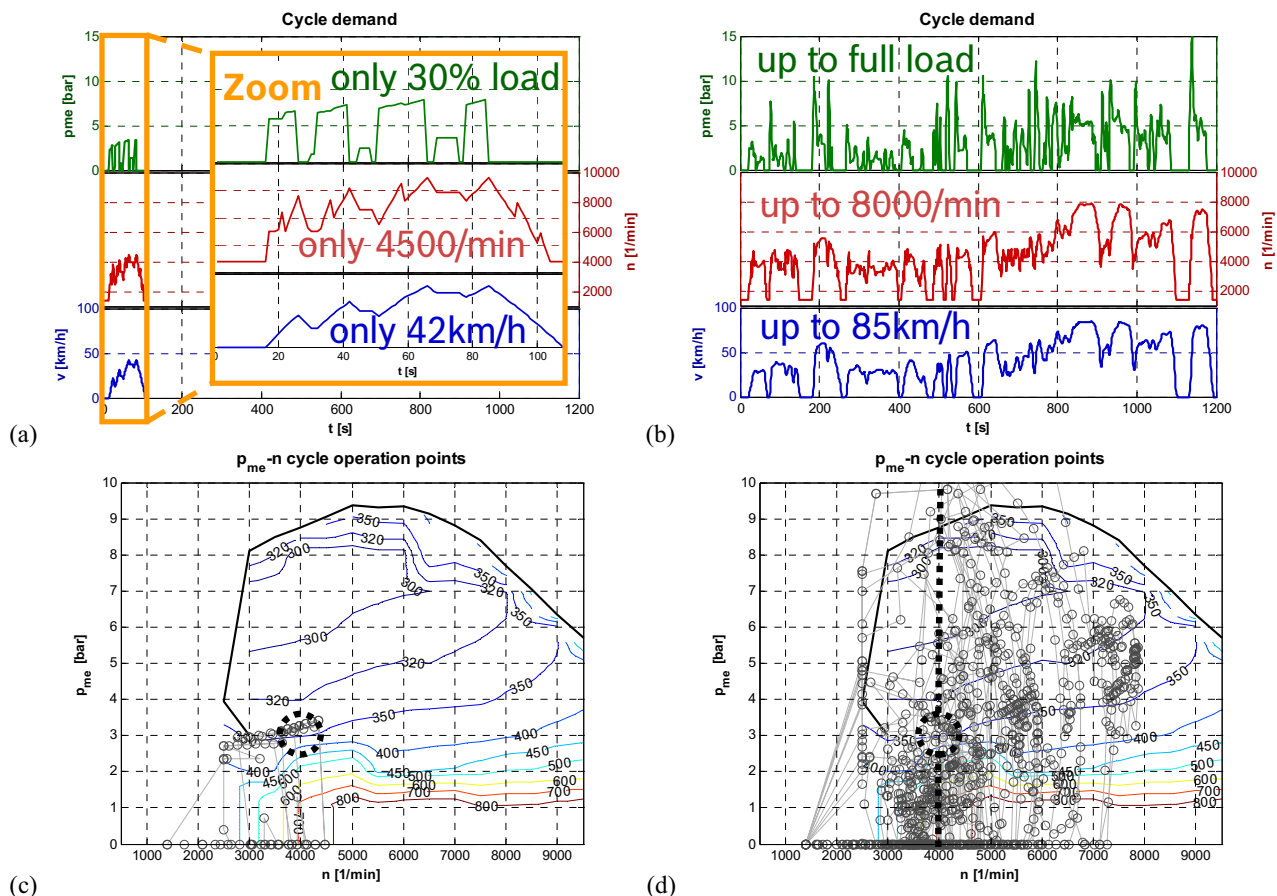


Figure 3. Fuel consumption test cycle simulation: IDC (a) and WMTC (b) vehicle velocities, engine speeds from underlying gear ratios and shifting patterns, and engine loads from accelerations, friction and aerodynamic drag. Resulting cycle discretization points for IDC (c) and WMTC (d) in speed/load stationary engine map.

driving pattern (see figure 3 b), resulting in engine speeds up to 8000/min and loads extending well up to full load. Discretizing the cycles in time steps of 1s yields clouds of quasi-stationary operating points within the speed-load engine operation map, which are visualized in figures 3 (c) and (d) for IDC and WMTC, respectively (along with bsfc iso-lines from the measurement at 165°C, figure 2 b). As can be seen, nearly all discretized points of IDC collapse to around 3bar bmep and a narrow speed range, while the WMTC almost completely fills the operating map. If one should pick a representative point for both cycles however, 4000/min 3bar bmep is an appropriate choice. WMTC shows dense clustering of operating points also below and above 3bar around 4000/min, so that the complete load sweep is of interest.

In figure 3 (d) some discretized points are exceeding the full load provided by the engine at WOT. If this was real the vehicle would not be able to follow the steepest accelerations. However it could also be an effect of insufficient temporal discretization of the very unsteady cycle data. As only very few points are affected, they may be well neglected though. A general uncertainty in the test cycle simulation arises from the necessity to estimate several vehicle parameters such as engine and wheel inertia, and vehicle drag coefficient and area. Therefore, a worst case estimate has been done employing respective data from

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a compact size car, showing no more than 20% higher loads. Besides, immediate fuel cut-off has been assumed in coasting, and the idling fuel consumption was set to 0.11/h.

Results of the fuel consumption test cycle simulation are summarized in figures 4 (a) in terms of fuel consumption in liters per 100km and (b) in terms of mileage in kilometers per liter, for IDC and WMTC at three different engine temperatures. One has to bear in mind that the simulation is providing best case estimates for fuel consumption, as it is neglecting distinct transient losses, e.g. higher HC emissions or retarded combustion phasing due to deviations in mixture quality (i.e. air-fuel ratio) during load steps. Also, cold start and engine heat up effects are not included.

One-sided error bars in figures 4 (a) and (b) indicate the worst case uncertainty from estimated vehicle parameters (as discussed earlier they were derived using very high values from a compact class car). These uncertainties stronger influence the WMTC result due to higher inertia and aerodynamic effects, increasing calculated fuel consumptions by up to 30%. Of course, those automotive parameters are clearly too high for a small engine, but part of the estimated uncertainty may outweigh neglected cold start and transient effects. Although there is considerable absolute uncertainty included in the fuel consumption test cycle simulation, it is mainly caused by systematic errors