Advances in Technology Innovation, vol. 2, no. 4, 2017, pp. 105 - 112

Numerical Study of the Operation of Motorcycles Covering the Urban Dynamometer Driving Schedule

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Received 02 September 2016; received in revised form 24 October 2016; accepted 25 October 2016

Abstract

It is shown, for the most challenging case of a cruiser motorcycle of low weight-specific and displacement-specific power and torque, that the tuning for better top end performances is irrelevant for the operation over the driving schedule used for certification. During the certification test, the engine only operates in the low speeds and loads portion of the map. It is concluded that any statement about motorcycles' pollution and fuel consumption should be only based on the measurement of their regulated emissions through proper chassis dynamometer tests, possibly redefining the driving schedule to better represent real driving conditions.

Keywords: motorcycles, pollutant emissions, driving cycles, aftermarket tuners, real driving conditions

1. Introduction

The actual operation of motorcycles covering emission and fuel economy certification cycles has been brought back to the attention of lawmakers, original equipment manufacturers and the general public by the recent ban of Harley-Davidson (HD) aftermarket Electronic Control Units (ECU) tuners in the United States of America (US). The use of aftermarket ECU tuners does not necessarily translate in worse regulated pollutant emissions as otherwise alleged by the US Environmental Protection Agency (EPA). Actually, these devices are more likely not relevant to any claim concerning emissions.

The ECU tuners are simple corrections of the fuel injection parameters to deliver air-to-fuel (AFR) ratio that may increase throttle response, power/torque output and overall ride ability. Their target is mostly the steady Wide Open Throttle (WOT) operation of the engine, i.e. the high load operation, as well as the high speed operation, plus the sharp accelerations.

5 years. They are not supposed to satisfy the emission rules of the time they were certified after the 5 years. Therefore, it does not make any sense to discuss the pollutant emissions of motorcycles older than 5 years with or without ECU tuners fitted. However, the retuning of an old engine may in principle offer the opportunity to introduce some improvements rather than declines in performances, power and torque, as well as fuel economy and pollutant emissions, as the old factory calibration does not necessarily represent the best choice of engine controlling parameter on a specific motorcycle more than 5 years old.

According to EPA rules, new motorcycles are tested on a driving cycle, where the engine delivers the power needed for the motorcycle to follow a low velocity schedule with everything but sharp accelerations and everything but high speeds. Hence, engines able to deliver much larger power and torque outputs operate significantly far from high load and high speed during the certification cycle, changing their load and speed much slower than what they could do, and reaching top power and torque outputs very far from their theoretical maximum.

For a gasoline fueled motorcycle having a three-way catalytic converter (TWC), port fuel injection and an oxygen sensor feed back to the ECU, any change of the controlling parameters returning a closer to stoichiometric air-fuel-ratio is not expected to translate in any worsening of the emissions. Only operating the engine richer for increased power and torque output at higher loads and speeds may have pollutant emissions and fuel economy downfalls in these operating points.

Fig. 1 presents the typical efficiency map of a catalytic converter. The emission reduction of a typical port fuel injected, homogeneous charge, and gasoline engine is based on the efficient operation of the TWC that require a close to stoichiometry air-to-fuel ratio. This is obtained by operating the fuel injectors to deliver a stoichiometric mixture as monitored by the exhaust oxygen sensor feed-back. Around the stoichiometric point (A/F=14.63), all the three pollutants (HC, CO and NO) are almost totally removed (>95 %).A slightly richer mixture translates in more CO and HC but not NO. A slightly leaner mixture translates in more NO but not CO and HC.

The engine operation in super sport, touring and cruiser motorcycles covering the EPA Urban Dynamometer Driving Schedule (UDDS, 40 CFR Part 86, Appendix I to Part 86 - Dynamometer Schedules) will be considered in the paper. Cruiser motorcycles are specific models designed with engines having low end specific performances, i.e. small displacement specific torque and power, small weight specific torque and power, low speed, if compared to touring and obviously super sport bikes. Cruisers have large torques only because of the large displacement.

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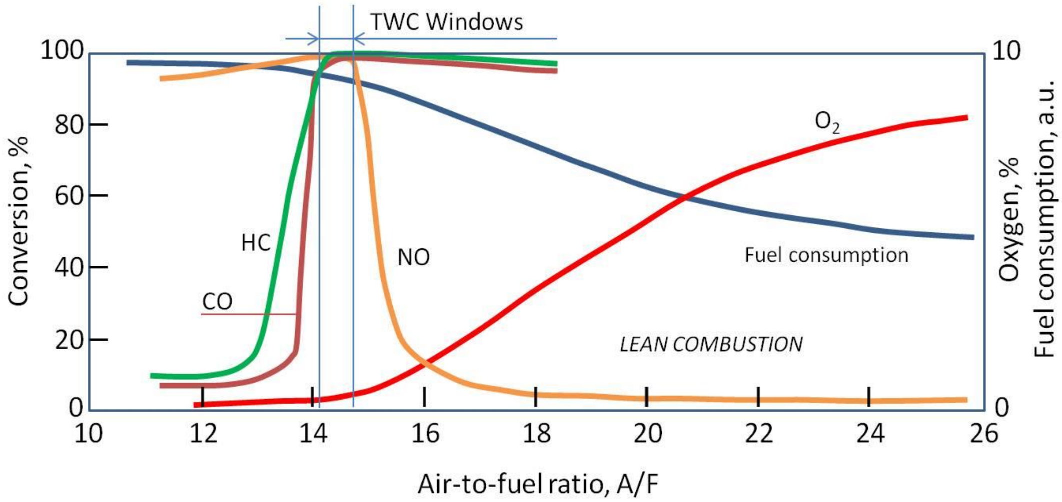

Fig. 1 Conversion curves for HC, CO and NO as a function of the air/fuel ratio, for a port fuel injected gasoline engine fitted with a TWC removed (>95 %)

2. EPA Motorcycles' emission rules

Street motorcycles' emissions are regulated under section 202 of the Clean Air Act. Background information on emission rules for motorcycles sold in the US may be found in [1, 2]. Table 1 (from [1]) summarizes the emission limits to be satisfied during chassis dynamometer testing of the motorcycle. Street motorcycles' emissions were regulated by a single unchanging set of standards for all model years from 1978-2005. In 2004, EPA established 2 tiers of conventional pollutant exhaust emissions standards. Tier 1 came into effect in 2006. In 2010, standards for Class III motorcycles were updated to Tier 2 standards.

Only class III motorcycles having a displacement in excess of 279 cm^3 are considered here, as the street motorcycle market is mostly made by super sport and touring bikes. Scooters are not considered.

Highway Motorcycles Exhaust Emission Standards only apply since 1978. Before 1978 there were no emission standards a motorcycle was requested to comply with. The standards applied first to new gasoline fueled motorcycles (since December 31, 1977). Then, later on, the standards were also applied to new, methanol-fueled motorcycles (since December 31, 1989), to new, natural gas-fueled and liquefied petroleum gas-fueled motorcycles (since December 31, 1996) and finally new motorcycles regardless of fuel (since 2006).

The table also includes useful life and warranty period. They are expressed in years and kilometers, and whichever comes first limits the need of compliance. The term "useful life" [3] does not mean that a motorcycle must be scrapped or turned over to the government after certain mileage limits are reached. It does not mean that a vehicle is no longer useful or that the vehicle must be scrapped once these limits are reached.

The term has no effect on the owners' ability to ride or keep their motorcycles for as long as they want. The current useful life for motorcycles with engines over 279 cm^3 is 5 years or 30,000 kilometers (about 18,640 miles), whichever first occurs. The test procedures for motorcycles from MY 1978 and later are detailed in 40 CFR Part 86 Subpart F. Fig. 2 presents the cycle. This cycle is characterized by low speeds.

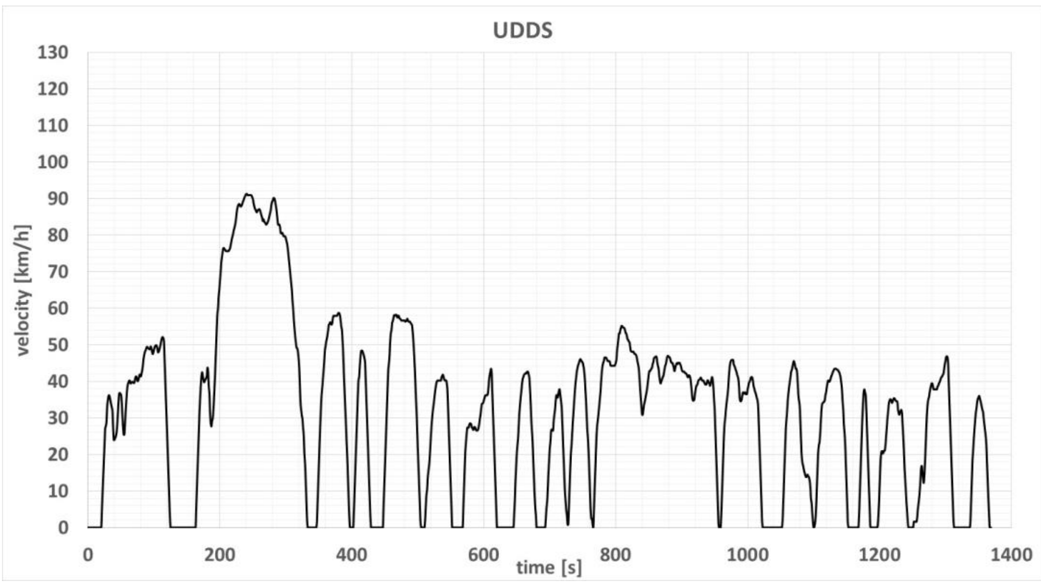

Fig. 2 UDDS velocity schedule

Table 1 Emission standards in the US (from [1])

Year	Class	Engine Size (cm^3)	HC (g/km)	HC + NOx (g/km)	CO (g/km)	Useful Life	Warranty
1978-2005	I	50-169	5.0	-	12.0	5 / 12,000	5 / 12,000
	II	170-279		-		5 / 18,000	5 / 18,000
	III	280+		-		5 / 30,000	5 / 30,000
2006+	I-A	< 50	1.0	1.4	12.0	5 / 6,000	5 / 6,000
	I-B	50-169	1.0	1.4	12.0	5 / 12,000	5 / 12,000
	II	170-279	1.0	1.4	12.0	5 / 18,000	5 / 18,000
2006-2009	III (Tier 1)	280+	-	1.4	12.0	5 / 30,000	5 / 30,000
2010+	III (Tier 2)	280+	-	0.8	12.0	5 / 30,000	5 / 30,000

3. HD Clean Air Act Settlement

The U.S. EPA and the U.S. Department of Justice (DOJ) announced on August 18, 2016 a settlement with HD companies, that required the companies to stop selling and to buy back and destroy “illegal tuning devices that in-crease air pollution from their motorcycles”, and to sell only tuning devices that are certified to meet Clean Air Act emissions standards. HD was also requested to pay a $12 million civil penalty and spend $3 million on a project to mitigate air pollution through a project to replace conven-tional woodstoves with cleaner-burning stoves in local communities.

EPA alleges that HD violated the Clean Air Act by manufacturing and selling about 340,000 devices, known as tuners that “allow users to change how a motorcycle’s engine functions”. According to EPA “these changes can cause the motorcycles to emit higher amounts of certain air pollutants than they would in the original configuration that HD certified with EPA”.

According to EPA, Since January 2008, HD manu-fac-tured and sold tuners that allow users to modify “cer-tain aspects of a motorcycles’ emissions control system”. According to EPA, these modified settings increase power and performance, but also increase the motorcycles’ emissions of hydrocarbons and nitrogen oxides (NOx).

The claim of violations is not based on any chassis dy-namometer measurements of the performances of motorcycles not having exceeded the useful life of 5 years or 30,000 km tested first without, and then with the kit fitted, to prove that a specific motorcycle model was not compliant because of the fitting of a specific kit.

4. Street Performance Tuners

The Screamin' Eagle Street Performance Tuner is a performance engine management system for electronic fuel injection (EFI) equipped Harley Davidson models [5-7]. The kit utilizes a wide-band oxygen sensor feedback to provide continuous air-to-fuel ratio (AFR) tuning cor-rections based upon riding conditions. The kit is aimed to deliver increased throttle response and torque, improved overall ride ability and performance, as well as a smoother and cooler running engine.

In many cases, the kit helps improving fuel economy, depending upon the bike’s configuration and the set-up of the AFR targets. AFR targets set to richer values than the stock levels to gain performance may result in moderate decrease in fuel economy. The Street Tuner permits lim-ited tunability within the emissions range to optimize drivability without compromising emission, but it is ob-viously intended to work outside the closed loop portion of the engine map where the AFR is ensured to be about stoichiometric for the best operation of the three-way-catalytic converter.

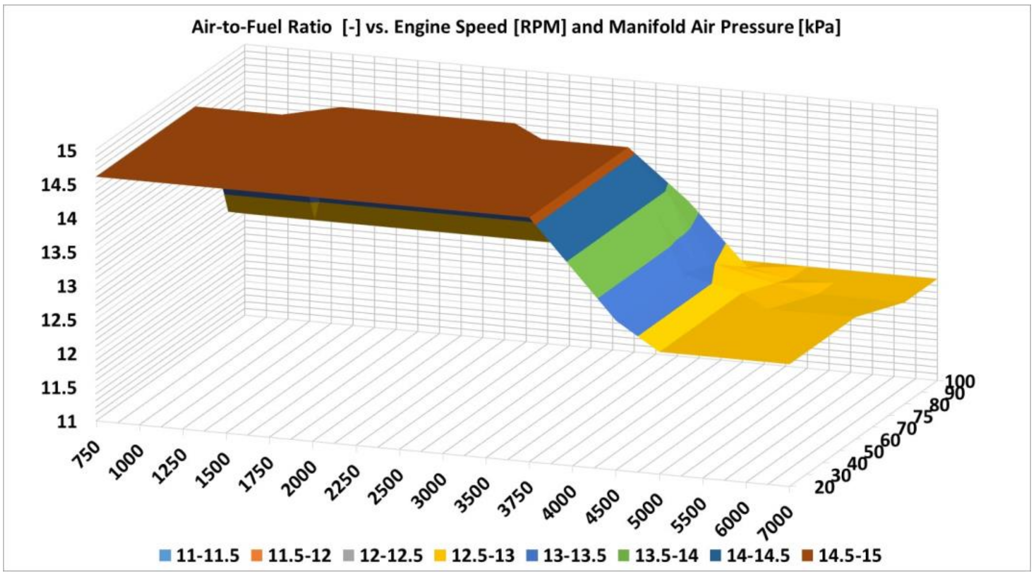

Fig. 3 Typical AFR map of a large HD cruiser with a Big V-twins engine

A typical tuners fuel map of a large HD cruiser is provided in [7] and reproduced in Fig. 3. The engine is a Big V-twins engine (Twin Cam 96, 96.96 cubic inch or 1,584 cm^3).These engines are characterized by much smaller specific torque and power density than the average super sport and touring bikes. Maximum power (but at the wheels, where it is typically 10-15% smaller than at the crank) is only 68 HP @ 5,000 rpm, while maximum torque (also at the wheel) is 110 N m @ 3,000 rpm. This engine powers motorcycles of 307.5 kg wet weight including oil and gas. Only above 80% MAP (roughly 50% throttle) and 4,000 rpm, where the engine does not operate during typical driving cycles including the certification cycle, the AFR is made rich.

Different "stages" of tuning are considered in [7]. The Stage 2 is an upgrade that includes new cams. The Stage 1 is upgrade also requiring exhaust and air cleaner. Both these upgrades are valid 50-state legal modification.

The Air Fuel Map of [7] has the cells in red with the stoichiometric 14.6 AFR in them over the low speed low load portion of the map that is relevant to the emission certification. Both stage 1 and stage 2 tunings do not affect this area. The ECU runs in closed loop mode looking at the oxygen sensor to satisfy the optimal composition of the exhaust gases for the TWC to reduce the tail pipe emissions.

In [7], the engine works closed loop to 3,750 rpm and to 80 kPa of manifold absolute pressure (MAP). The ECU uses manifold pressure from the MAP sensor to determine the actual engine load rather than the throttle. Throttle position does not relate linearly to the MAP sensor reading. 80 kPa MAP is typically around 40% throttle. Ref. [7] assumes the OEM AFR table is same or very similar of Fig. 3, but may obviously differs outside the 3,750 rpm and 80 kPa area. Therefore, tuners are possibly delivering same AFR vs. MAP and speed of the OEM in the low MAP and low speed area of emissions' control, and then they differ.

It is worth to mention that usually steady state AFR maps do not need fuel rich conditions except than approaching WOT conditions, i.e. close to the maximum loads for any speed. The fuel rich mixture at speed exceeding 3,750 rpm any load seems quite questionable.

The tuner operates rich everywhere out of the closed loop area very likely because the injection system is everything but effective in delivering the amount of fuel needed when the throttle opens sharply. Even racing engines these days go rich only approaching WOT conditions at any speed, as even these extreme engines run slightly lean part load to reduce unnecessary fuel consumption.

In addition to the AFR map, Ref. [7] also provides the bias tables and the Ignition Advance map for the HD Stage 1 and Stage 2 bikes.

It is not the object of the paper to enter more in details of the specific tunings, only to show in the next section how the operation of a motorcycle over a driving schedule for emission certification never utilizes the high loads or high speeds parts of the map that are the ultimate goal of tuning an engine for mostly improving power and torque output.

5. Method

Map based computer models are used to investigate the operation of an engine when the motorcycle is covering a driving schedule. Vehicle Driving Cycle Simulations have been around for many years. Basic solutions of the New-ton's equation of motion for a vehicle following a pre-scribed velocity schedule returns the instantaneous power requested to the engine with a simplified modelling of transmission losses, aerodynamic and rolling resistance, and vehicle and engine inertia. Transmission ratios then also return the speed requested to the engine. Interpolating the steady state maps of brake specific fuel consumption or specific emissions, it is then possible to evaluate the fuel consumption and the pollutant emissions on a driving cycle. For cold start, correction curves are needed. For the interested reader, these simulations are presented in [12-24].

To simplify, a driving cycle simulator solves the Newton's equation of motion. If $F_{p,e}$ is the engine propulsive force and $F_{b,f}$ is the friction brake force, it is:

$$F_{p,e}-F_{b,f}-F_a-F_r= m\cdot a \tag{1}$$

with m the mass, a the acceleration, =dv/dt, with v velocity of the motorcycle and t the time, F_a the aerodynamic drag force, $=½\cdot\rho\cdot v^2\cdot C_D\cdot A$, with ρ air density, C_D drag coefficient (always positive for a retarding force) and A reference area, F_r the rolling resistance force, an empirical function of the speed of the motorcycle. In terms of powers, by multiplying for the speed of the motorcycle, it is then

$$P_{p,e} -P_{b,f} = m\cdot v\cdot dv/dt +½\cdot\rho\cdot v^3\cdot C_D\cdot A+P_r \tag{2}$$

The above propulsive power is computed at the wheel. The power of the engine at the crankshaft P_b is larger than the power at the wheel $P_{p,e}$ to include the transmission efficiency η. The speed of rotation of the engine is then obtained by the speed of the motorcycle by considering tire radius, gear and gear ratios. The gear is determined by an upshift/downshift strategy. From a velocity schedule v(t), it is thus possible to compute the instantaneous power $P_{p,e}$ and $P_{b,f}$, and from $P_{p,e}$, then the power P_b and the speed N that the engine must provide.

When $m\cdot v\cdot dv/dt +½\cdot\rho\cdot v^3\cdot C_D\cdot A+P_r \geq 0$, equation (2) returns $P_{p,e}$ with $P_{b,f}$=0. When $m\cdot v\cdot dv/dt +½\cdot\rho\cdot v^3\cdot C_D\cdot A+P_r$ <0, equation (2) returns $P_{b,f}$ with $P_{p,e}$=0. $P_{b,f}$ represents in this case not only the actual power dissipated in the friction brakes $P^*_{b,f}$, but also the negative power requested to motor the engine at the given speed N (engine brake).

Engine performances are typically defined in terms of power P_b, torque T_b and brake mean effective pressure BMEP. The power P_b is proportional to the product of torque T_b and speed N. The BMEP is proportional to the ratio of torque T_b and total displaced volume V_d. Engine data are provided as the wide open throttle torque output T_b vs. speed N, plus the maps of specific fuel consumption and pollutant emissions vs. BMEP and N. This way the driving cycle simulator returns the fuel economy and the pollutant emissions during warmed-up cycles, with empirical penalty functions needed for cold-start cycles.

The model simulates a motorcycle performing a test cycle. The UDDS is considered. The cycle is everything but aggressive, and it is characterized by mostly low speed. In the UDDS cycle, Fig. 2, only in one of the acceleration, cruise and deceleration schedules it is requested a bike velocity of 90 km/h, and in only 3 other areas the bike reaches a speed above 50 km/h but less than 60 km/h.

Figs. 4, 5 and 6 present reference data of BMEP, torque and power vs. engine speed and throttle opening % for the typical large cruiser considered here, having a low displacement specific power and torque, low maximum speed. The engine is 1,300 cm^3 and it is fitted on a heavy motorcycle of weight 380 kg including the driver during the simulated chassis dynamometer test.

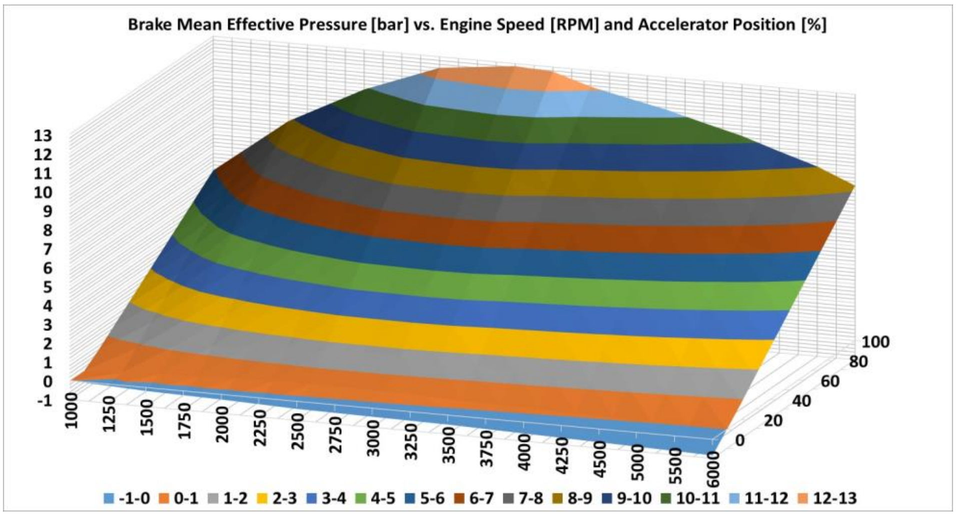

Fig. 4 Typical Brake Mean Effective Pressure map of a large cruiser motorcycle

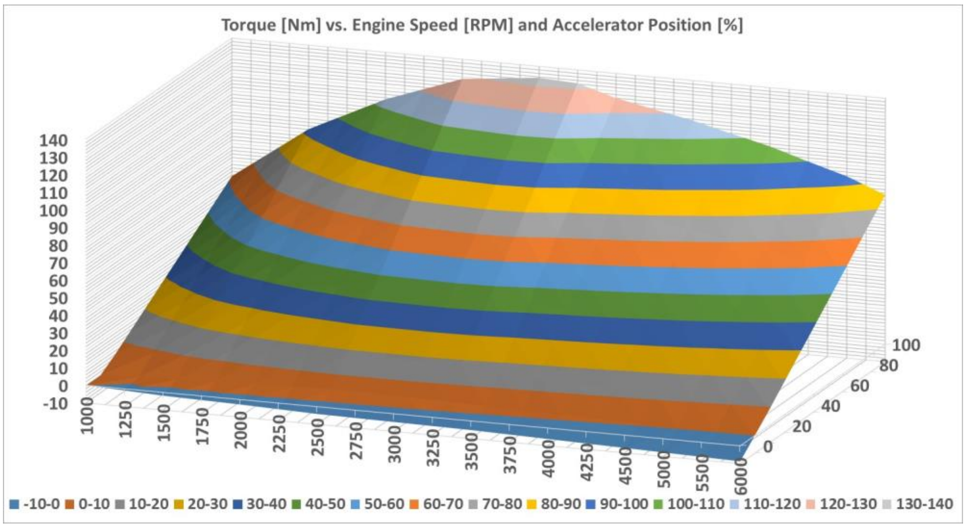

Fig. 5 Typical torque map of a large cruiser motorcycle

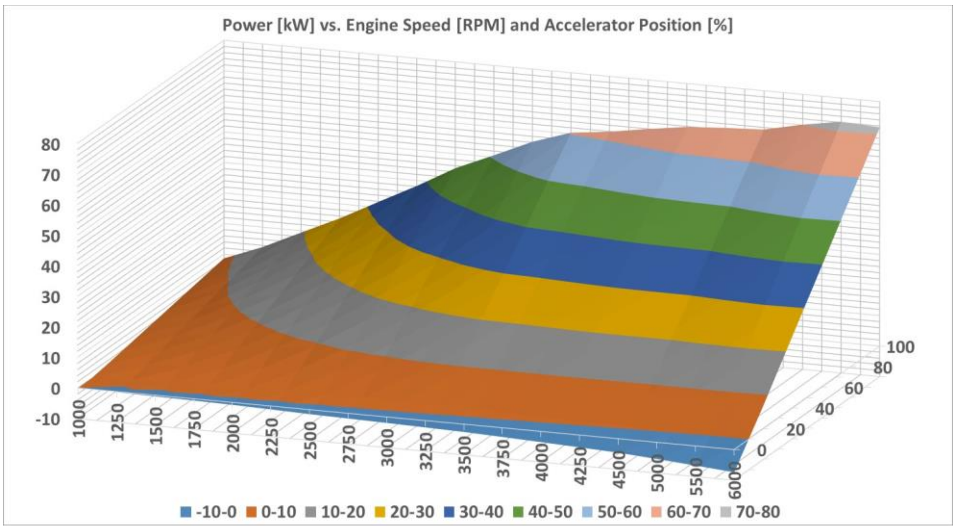

Fig. 6 Typical power output map of a large cruiser motorcycle

Table 2 Model parameters

Rated Engine Speed	6,500	RPM
Upshift	4,000	RPM
Downshift	2,000	RPM
Ratio of 1st Gear	9.312	
Ratio of Gear 2	6.421	
Ratio of Gear 3	4.774	
Ratio of Gear 4	3.926	
Ratio of Gear 5	3.279	
Ratio of Gear 6	2.79	
Motorcycle Weight	377	kg
Engine Power at Rated Speed	55	kW
Tire Rolling Radius	457.2	mm
Tire Rolling Resistance Factor	0.0122	
Engine Displacement	1,304	cm^3
Engine Inertia	0.05	$kg\text{-}m^2$
Frontal Area	0.2	m^2
Coefficient of Drag	0.6	
Wheelbase	2	m
Initial Engine Speed	1,500	RPM
Initial Gear Number	1	

Table 2 presents the relevant model parameters, idle speed, rated engine speed and engine power at rated speed, upshift and downshift speed, that may differ at every gear, ratios of 1st to 6th gear (if a 6 gear transmission is considered as it is in this case), motorcycle weight, tire rolling radius, tire rolling resistance factor, engine displacement, engine inertia, frontal area, coefficient of drag, wheelbase, initial engine speed and gear number.

6. Results and Discussion

The engine map BMEP (brake mean effective pressure) vs. engine speed at different loads is the one of Fig. 4, where the load is expressed in terms of acceleration position (AP).

Fig. 7 presents the computed operating points, while Fig. 8 presents the computed time distribution on engine map of the operating points of a large cruiser motorcycle covering the UDDS cycle. The engine operates below 2.5 bar BMEP and below 4,000 rpm over the cycle. Every map point above these values has time distribution zero, i.e. whatever could be the emission in these points, and this has no effect on the regulated emissions. The most part of the time the engine is idling. Then, when delivering an output, the engine is always operating well below 2.5 bar BMEP and 3,750 rpm.

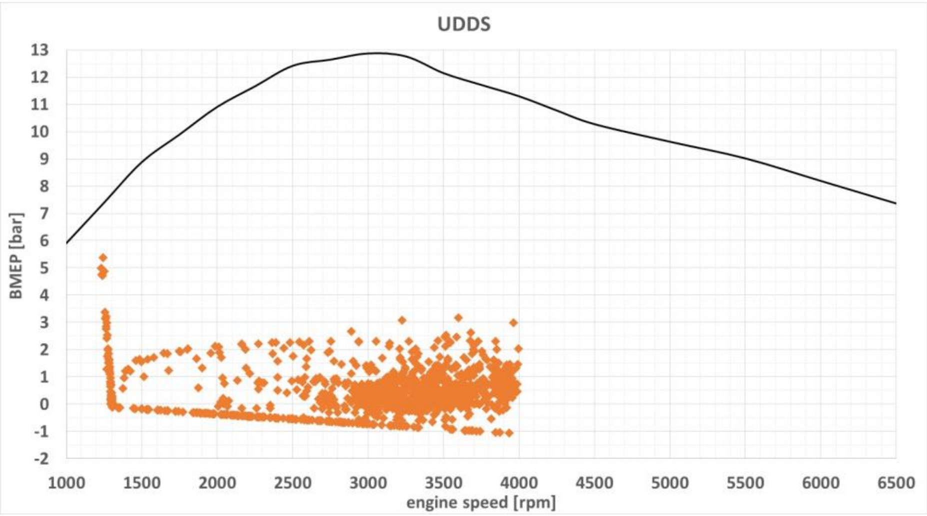

Fig. 7 Typical operating points of a large cruiser motorcycle covering the UDDS cycle

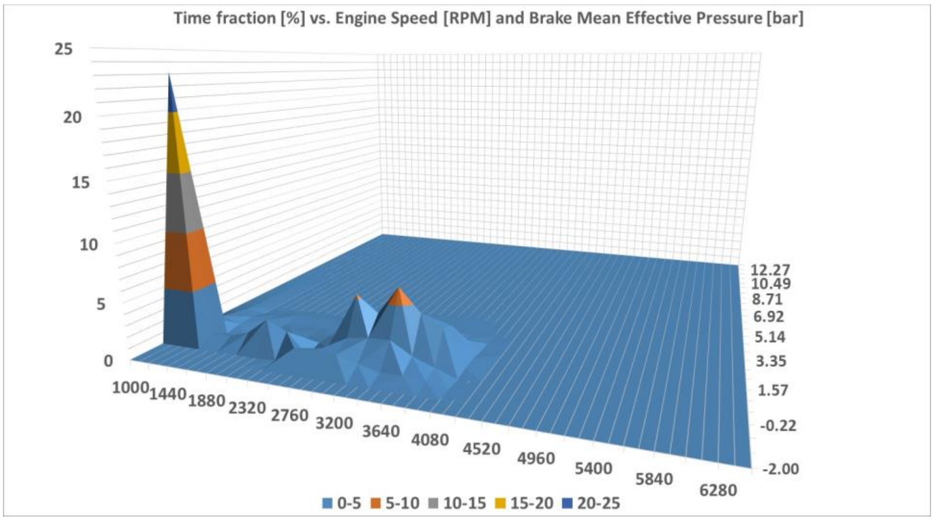

Fig. 8 Typical time distribution on engine map of the operating points of a large cruiser motorcycle covering the UDDS cycle

In terms of performances, today's super sport, touring and cruiser bikes may have very high specific power and torque densities. As HD does not provide online information about power and torque figures, typical performance parameters are proposed for other manufacturers.

The 998 cm^3 Yamaha YZF R-1 [9], one of the most powerful super sport bikes, has for example 200 HP/liter revving 13,500 rpm. The specific torque is less exceptional, as the result of the tuning for high speeds, but still 112 N m/liter revving 11,500 rpm. The wet weight including full oil and fuel tank is 199 kg. This bike has a top speed of 300 km/h. As an example of touring bikes, the 1,298 cm^3 Yamaha FJR1300A [10] has 112 HP/liter revving 8,000 rpm and 106 N m/liter revving at 7,000 rpm. The wet weight (including full oil and fuel tank) is 289 kg. This bike has a top speed of 245 km/h. Finally, as a typical cruiser, the 1,304 cm^3 Yamaha XVS1300 Custom [11] has 56 HP/liter revving 5,500 rpm and 79 N m/liter revving 3,000 rpm. The wet weight including full oil and fuel tank is 293 kg. This bike has a top speed of 175 km/h. Therefore, in normal driving correctly accounted for emission regulations, motorcycles work very far from their potentials.

The most part of the motorcycles in the super sport and touring classes are usually more performant than the cruisers. They have much larger power and torque to weight ratio, as they are much lighter, and also have much larger displacement specific power and torque. The most part of the super sport and touring motorcycles are therefore working even farther away from their highest speed and highest load points where they may operate off-stoichiometry during typical driving cycles including the UDDS emission cycle. The results proposed in the previous section are therefore a worst case scenario.

7. Conclusions

It is pure speculation to claim that ECU tuners can cause the motorcycles to emit higher amounts of certain air pollutants than they would in the original certified configuration without even mentioning the specific motorcycle where the tuners are fitted.

In principle, ECU tuners are not expected to affect any regulated emission.

If fitted to motorcycles having exceeded the useful life, presently defined as 5 years or 30,000 kilometers (about 18,640 miles) whichever first occurs, as these motorcycles are not presently expected to comply with any emission rule, having or no the tuners makes no difference.

For new motorcycles, the ECU tuners are expected to modify the AFR only at the higher loads and speeds that are very far from the area of operating points that are designed closed loop stoichiometric, to comply with the emission rules properly using the TWC.

Old and new motorcycles cannot be claimed a-priori not compliant without providing any evidence of failure to perform as required by regulation, and obviously they cannot be claimed not compliant if there is no rule to comply with. Any statement about motorcycles' pollution and fuel consumption should be only based on the measurement of their regulated emissions through proper chassis dynamometer tests.

The results emphasize the importance of real world driving in motorcycles. The paper shows that the ECU tuners have no effect on the presently regulated pollutants emission, even if modifying the AFR certainly lead to change in emission performance of the vehicles. While the ECU tuners may not affect the pollutants emission under well-constraint laboratory certification tests, they certainly change the emissions over real world driving. The paper therefore emphasizes the importance of the inclusion of real world driving in emission certification tests.

The introduction of better emission certification tests will ultimately translate in superior fuel conversion efficiencies of the internal combustion engine over the full range of loads and speeds, for example also simply adopting jet ignition and direct injection [25], plus the hybridization of the power train, for example with a flywheel or a Li-ion battery based kinetic energy recovery system [26].

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