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Influence of mathematical simplifications on the dynamic and energetic performance of an engine/motorcycle integrated model

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Abstract

Brazil is a major producer and consumer of motorcycles. In this context, the Department of Mechanical Engineering at the Federal University of Pernambuco offers three two-wheeled courses: Studies on Bicycles and Motorcycles (45 h, graduate students), Propulsion of Bicycles and Motorcycles (45 h, graduate students), and Motorcycle Engineering (60 h, under graduate students). All of them present a greater or lesser mixture of general topics (e.g. accidents, culture, market, history) and technical ones (e.g., technology description and mathematical modeling). On those courses, the calculations are made using empirical correlations, commercial packages, and also simple methods, which, although quantitatively weaker, have both didactic and theoretical advantages, as they consider the essence of the phenomena and reveal the strongest relations between the variables. In this paper, we present an integrated engine/motorcycle simple model that permits the manipulation of parameters, such as the combustion time, heat losses, drag and inertial resistances, gear shifting and others. Those model parameters are then varied to study their influence on the motorcycle behavior. Manipulating this model, students learn that both engine and motorcycle inefficiencies have the same order of influence on motorcycle economy, ethanol is less volumetrically efficient than gasoline, the change of sprockets can increase the maximal speed while deteriorating the mean speed, and other interesting practical concepts. The success of the courses can be gauged by the students' enrollment, by the professors'

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evaluation by the students, class participation, and by the strong commitment of the students to the final projects. Other highly probable cause for the success is the motorcycle itself, always a passionate subject for young people in general, and mechanical engineers in particular.

Keywords

Internal combustion engine, motorcycle, vehicle dynamics

Introduction

Brazil is a major producer of motorcycles, with 1.5 million units sold in a year and a fleet of about 20 million. In general, Brazilian society sees the use of motorcycles in a dichotomous way. On the one hand, people approve the increased mobility in the congested streets and the fast delivery of goods. On the other hand, the country severely suffers with the deaths – 10,000 motorcyclists die per year.

In this complex context, we offer three courses at the Mechanical Engineering Department at the Federal University of Pernambuco, Brazil, related to motorcycles. *Studies on Bicycles and Motorcycles* is a 45-h interdisciplinary course for graduate students, in which we study two-wheeled vehicles from the most varied points of view: accidents, tourism, market, industry, design, prejudice, culture, work, social and political organization, infrastructure and technology. In a second 45-h course for graduate students, *Propulsion of Bicycles and Motorcycles*, we study several mathematical models for the simulation of the engines (internal combustion engines, electric engines and human propulsion), the vehicles (motorcycles and bicycles) and the traffic involving those two-wheeled vehicles. Those simulations are used to quantify vehicle flow on a road, fuel consumption, CO_2 emissions, costs and, in the future we hope, pollutants and the risk of accidents.

In the present paper, we are going to discuss specifically a third course, *Motorcycle Engineering*, offered for undergraduate students. This 60-h course is divided into five modules: General Topics[1–7] (e.g. market, accidents, culture), 8 h; Technologic Description,[8–10] 8 h; Engine Modeling,[11,12] 16 h; Vehicle Dynamics Modeling[13–17] (i.e. modeling of the whole behavior of the motorcycle), 16 h; and Vehicle Components Modeling[14,18,19] (e.g. steering, suspension, frame and tires), 12 h. The course began in 2010. It is elective, which means that enrollment is not compulsory for all the students, and it is heavily based on the use of computational models both of the engine behavior and motorcycle dynamics. The use of computational models for teaching is reported in several papers as, for example, Zueco[20] in the thermodynamics modeling of an ICE (internal combustion engine), and Tian and Abraham,[21] with the application of CFD to study the charge movement, but the use of integrated engine, dynamics and even in some instance traffic models is very uncommon.

An important feature is that the actual course is strongly based on the interests and training of its two professors. They minister basic engineering courses (e.g. Applied Thermodynamics and Mechanisms), so the basic phenomena (e.g. combustion, aerodynamic drag, tire friction with the ground, kinematics of the suspension mechanism) are the main subjects of the course. Additionally, they use mainly computational modeling in their research, so the course is majorly computational – although this is also caused by budget limitations. Both professors are daily users of motorcycles, so the discussions of the models results and of the theories are always linked to the actual use of motorcycles.

From a pedagogical point of view, the course uses the study of motorcycles to integrate the knowledge the students acquired in other courses (e.g. Thermodynamics, Fluid Mechanics, Mechanisms, and Dynamics). In addition, the course presents engineering methods that are not mandatory in Federal University of Pernambuco (e.g. Finite Differences and Finite Element Methods). Thirdly, we always try to contextualize the problems we are studying. For example, in the study of the engine combustion, we discuss the implications on climate change; in the study of the motorcycle dynamics, we stress riding safety; and so on.

In this paper, we will focus only on the mathematical modeling of the assembly engine/motorcycle. In particular, we want to show how we use several levels of approximations to teach the students the relative importance of each idealization. In the next section, we are going to present the *real engine* and the *real vehicle* models. Obviously, they are not "real", but are the more realistic among all the models we are going to study. In the third section, first we show how those models can be used to study a motorcycle being tested for acceleration and fuel consumption. After, we progressively simplify those *real* models to reach an *Otto engine*, a *perfect engine*, a *variable engine*, a *perfect motorcycle*, and a *variable motorcycle*. Those engines and motorcycles are then (computationally) tested in order to study the influence of each parameter on the final behavior of the vehicle. For example, is the engine irreversibility or the motorcycle mass inertia the main "culprit" of the high fuel consumption? What would have greater impact, the swap of an electric motor for the internal combustion engine or the use of a highly aero efficient motorcycle body? What is the influence of the coefficient of heat transfer on the motorcycle consumption?

Although in this paper we are going to evaluate the motorcycle behavior only from the point of view of time and fuel consumption to complete a circuit on the virtual test track, in the course, we also calculate costs and CO_2 emissions. In all the studies shown here, the "rider" is always free to choose the motorcycle speed (limited by the engine and by the resistive forces, of course), but in the real world, the motorcycle speed is mainly restricted by the traffic. In the *Engineering Motorcycle* course, we perform such traffic studies, but they will not be presented here due to lack of space.

Mathematical modeling

In the Engine Modeling module of the course, we first present the thermodynamic model of the internal combustion engine. Then we perform more detailed simulations using commercial packages, and, finally, we present empirical correlations for the calculation of the power curve and the efficiency map of the engine. We also discuss how those curves would be in the case of vehicles with human or electric propulsion. In this specific paper, we will show only the thermodynamic model of the internal combustion engine.

In the Vehicle Modeling module, the engine's power curve (regardless of how it was obtained or of which type of propulsion it belongs to) is inserted into the motorcycle model, which takes into account both rider-controlled forces (propulsion and braking) and resistive forces (inertia, aerodynamic drag, rolling resistance and gravity). The motorcycle model is then coupled with a rider model, which, through the activation of the throttle, brake and gear shift, tries to reach a certain known desired speed curve – for example, to accelerate from 0 to 60 km/h in 20 s or to maintain a constant cruising speed despite of the road incline. In the postgraduate courses, the desired speed curve is obtained from a traffic model.

The engine model is built up from six calculation steps: (a) initial mass and composition, (b) cylinder volume, as a function of the crankshaft angle, (c) chemical composition of the gases, according to the crankshaft angle, (d) pressure and temperature, according to the crankshaft angle, (e) mean power and fuel consumption for the whole cycle, according to an specific angular velocity (r/min), (f) maximum power curve, as a function of the engine r/min, and efficiency map, as a function of throttle position and engine r/min.

The initial composition of the fuel air mixture is determined taking into account the composition of fresh air, fuel type and proportion in the mixture, and residual gases. The mass of the air/fuel mixture is calculated taking into account the volume of the cylinder, engine r/min and volumetric efficiency, which depends on the valve opening and throttle position.

The cylinder volume is calculated according to the geometry of the cylinder and slider crank mechanism[22] (Figure 1) by equation (1), where $\mathcal{V}_i$ is the volume for the crank angle θ_i, $\mathcal{V}_{cam}$ the residual volume of the combustion chamber in the top dead center, B the cylinder bore, R the crank length, and L the connecting rod length (the subscript i stands for the crank position).

$$\mathcal{V}_i = \mathcal{V}_{cam} + \frac{\pi B^2}{4}\left(R + L - R\cos\theta_i + L\sqrt{1 - \frac{R^2\sin^2\theta_i}{L^2}}\right) \tag{1}$$

Given the initial mixture composition, in the third step, we determine the composition for any crank angle. At any point in the cycle, we consider that the composition inside the cylinder is given by equation (2), being governed by the extent of reaction, γ, that represents the proportion in which the reactants have been transformed in products of the reaction. The subscript *res* refers to the number of moles in the residual gases, *reac* to the number of moles in the admission mixture of reactants, and *prod* to the number of moles of a certain species on the products of

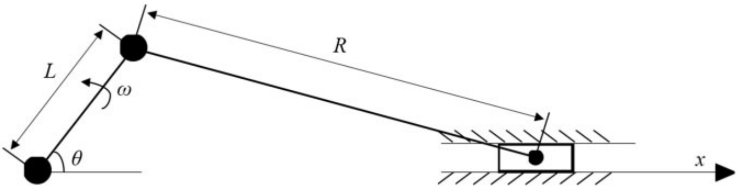

Figure 1. Slider crank mechanism.

the combustion. The number of moles of each component is determined by stoichiometric calculations, as a function of the $C_xH_yO_z$ fuel, percentage of theoretical air, residual gases and initial mass.

$$\begin{aligned}&\text{Charge composition} =\\&(1-\gamma)\left[n_{N_2,res}N_2 + n_{O_2,res}O_2 + n_{CO_2,res}CO_2 + n_{H_2O,res}H_2O + n_{N_{CO},res}CO\right]\\&+(1-\gamma)\left[n_{C_xH_yO_z,reac}C_xH_yO_z + n_{O_2,reac}O_2 + n_{N_2,reac}N_2\right]\\&+\gamma\left[n_{N_2,prod}N_2 + n_{O_2,prod}O_2 + n_{CO_2prod}CO_2 + n_{H_2O,prod}H_2O + n_{N_{CO},prod}CO\right]\end{aligned} \tag{2}$$

The given curve of the extent of reaction, γ, is formed by four ranges. In the first part ($\gamma = 0$), the composition of the initial charge remains unchanged, in the second part ($0 \leq \gamma \leq 0.1$), the reaction advances 10% (delay combustion), in the third part ($0.1 < \gamma \leq 1.0$), the reaction advances the other 90% (main combustion), and in the fourth part ($\gamma = 1$), only the products remain. The difference between the second and the third range is that, in the second, the 10% combustion occurs for a constant time interval, independently of the engine r/min, and, in the third range, the final 90% of the combustion occurs in a constant angle interval.[11] In this way, we can simulate both the beginning of the combustion, that is primarily governed by the reaction kinetics, and the main combustion, that is governed mainly by the charge vorticity.

Given the composition and volume for each angle, as well as the initial pressure and temperature, we can now calculate the temperature and pressure for each angular position of the crankshaft. The first step is to calculate the initial internal energy of the charge, by equation (3), considering the charge as a mixture of perfect gases (the subscript j stands for the substances) each one with specific heat ($\bar{c}_{vo_j}$) and a known internal energy of formation ($\bar{u}_{f_j}$) given for T_0.

$$U_1 = \sum n_{j,1}\left[\bar{u}_{f_j} + \bar{c}_{vo_j}T_1 - \bar{c}_{vo_j}T_0\right] \tag{3}$$

For each angle of the crankshaft, considering the First Law of Thermodynamics, equation (4), we can calculate the internal energy for the next position (the subscript i stands for the crank position).

$$U_i = U_{i-1} + Q_i - W_i \tag{4}$$

The previous equation can be modified into equation (5)

$$U_i = U_{i-1} + hA_i(T_{cool} - T_{i-1})\Delta t - p_{i-1}(\mathcal{V}_i - \mathcal{V}_{i-1})\varepsilon_i \tag{5}$$

where the global heat transfer coefficient h is calculated by an empirical correlation,[23] the heat transfer area A_i is calculated as a function of the piston position, T_{cool} is the temperature of the cooling fluid, T_i the average temperature of the gases in the combustion chamber, p_i is their pressure and $\mathcal{V}_i$ is their volume. The compression coefficient, ε_i, is equal to the isentropic expansion coefficient in the case of expansion, and equal to the inverse of the isentropic expansion coefficient in the case of compression.

Knowing the internal energy, given by equation (5), and the composition, given by equation (2), we can calculate the temperature with equation (6) and the pressure with equation (7).

$$T_i = \frac{U_i - \sum n_{j,i}\left(\bar{u}_{f_j} - \bar{c}_{vo_j}T_0\right)}{\sum n_j \bar{c}_{vo_j}} \tag{6}$$

$$p_i = \frac{n_{tot,i}\bar{R}T_i}{\mathcal{V}_i} \tag{7}$$

The choice of a constant $\bar{c}_{vo_j}$ greatly simplifies the numerical solution of the temperature (equation (6)). In some editions of the course, we implemented an engine model with a variable $\bar{c}_{v_j}$, but the increased complexity of equation (6) did not bring new insights to the students. Additionally, the time spent to explain the new numerical subtleties stole precious time of the general theory and analysis of the results. Thus, we returned to the constant $\bar{c}_{vo_j}$ engine model. It is clear that using equations (6) and (7), we are considering the charge as a mixture of ideal gases, where $\bar{R}$ is the universal constant of gases (molar basis).

Summing the product $p_i\Delta\mathcal{V}_i$ for the whole cycle, as shown in equation (8), results in the mechanical power delivered by the engine, where ω is the engine r/min, and $\dot{P}_f$ is the power [W] dissipated by the friction in the entire path between the piston and the output shaft of the engine.

$$\dot{P}_{eng} = \frac{\omega}{120}\sum p_{i-1}(\mathcal{V}_i - \mathcal{V}_{i-1})\varepsilon_i - \dot{P}_f \tag{8}$$

When equation (8) is used in a condition of fully open throttle, we call the power curve as $\dot{P}_{max,eng}$, which is function of the engine r/min. In this model, we consider that the friction power, $\dot{P}_f$, is a straight line ranging from 0.1 of the peak engine power, for low revs, to 0.25 of the peak engine power, for high revs.

The engine r/min influences power in four ways. First, directly, as seen in equation (8), in which the engine r/min multiplies the summation for one cycle. Second in the friction power, also in equation (8), which grows linearly with the engine r/min. Third in the evolution of the pressure, since the higher the engine r/min, the lower the Δt and, consequently, the lower the heat loss per cycle (equation (5)). Fourth, the engine r/min influences the power through the volumetric efficiency during the admission of the air fuel mixture.

The engine efficiency is calculated by equation (9), that takes into account the engine curve, $\dot{P}_{eng}$, and the fuel heat value, $\bar{H}_{C_xH_yO_z}$.

$$\eta_{eng} = \frac{\dot{P}_{eng}}{n_{C_xH_yO_z}\bar{H}_{C_xH_yO_z}\frac{\omega}{120}} \tag{9}$$

With this engine model, equations (1) to (9), we try to create a qualitatively complete model that contains the essence of the engine, although it cannot be used quantitatively. The following phenomena should additionally be considered in a quantitative model: load movement, pollutant production, combustion as a function of charge motion, variable isentropic efficiency, inlet and outlet gas dynamics, gas wave resonance, ignition control, injection control, water content in the air, specific heat varying with the temperature, and others. Later in the course, it is necessary to introduce more realistic models to the students, since they are more precise and more applicable to actual engineering problems. At that moment, we prefer to use commercial packages rather than to complicate the simple model here presented. One should notice that those more detailed models on the one hand present more interesting results, but on the other hand have a closed or, if not closed, a computational model so complex that we cannot make the essence of each individual phenomenon explicit. We believe that sometimes a simpler model provides the students with a deeper understanding of the problem than a more detailed one, thus the students should be in contact with both simpler and more detailed models in their studies.

The motorcycle movement is modeled by Newton's Second Law, expressed mathematically by equation (10) and graphically by Figure 2. The first term on the left is the inertia, where m is the total mass (vehicle + rider + occasional pillion), V is the motorcycle speed, and t is the time.

$$m\frac{dV}{dt} = \frac{\alpha\dot{P}_{max,eng}}{\eta_{trans}V} - \beta\mu mg\cos\varphi - k_A(V-W)^2 - C_R mg\cos\varphi - mg\sin\varphi \tag{10}$$

The first term on the right is the tractive force, where α is the throttle coefficient, $\dot{P}_{max,eng}$ the maximal engine power for a specific engine r/min (calculated by the engine model, equation (8)), and η_{trans} the transmission efficiency. The next term is the breaking force, where β is the breaking factor used by the pilot, μ the friction coefficient between tire and road, and φ is the inclination of the road. The third factor is the aerodynamic drag force, in which the constant k_A ($=1/2\rho C_D A$) considers the fluid density, the frontal area and the vehicle shape, and W is the wind speed. In the fourth term, the model takes into account the rolling resistance, that is

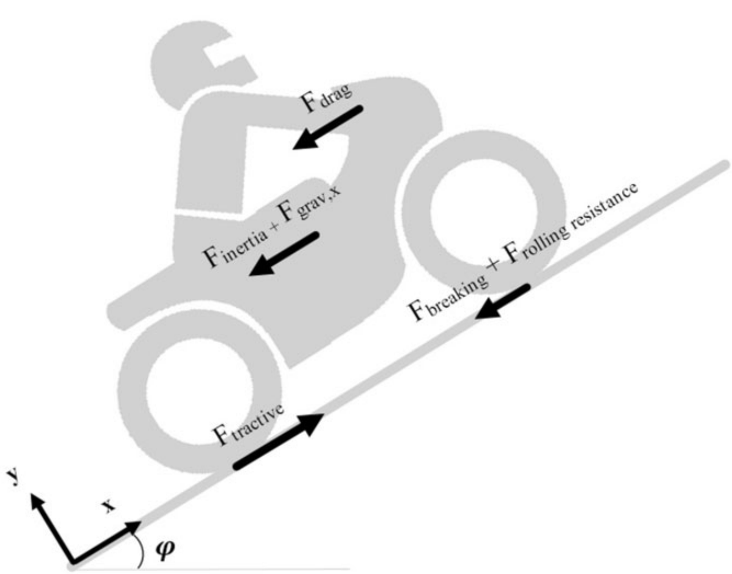

Figure 2. Balance of forces acting on the motorcycle.

basically the force to deform the tire, characterized by the coefficient C_R. The last term is the gravitational resistance. Since this study is in a straight line, equation (10) can be used for cars,[18,24] motorcycles[13–15] and bicycles,[16,17] given the correct parameters.

The relation between the engine r/min, needed to calculate $\dot{P}_{max,eng}$ (equation (8)), and the vehicle speed, V, is given by the transmission ratio, the wheel diameter and the choice of the gear by the rider model. The transmission ratio being discrete, with a finite number of gears, and hysteretic, since the rider shifts up or down the gears at distinct engine r/min, makes it very difficult to use analytical techniques to solve the differential equation. Thus, equation (10) is solved by the finite differences method, using the following steps. First, a desired speed curve is specified, generally given by the traffic condition and the preferences of the rider. For every time instant, we use equation (10) to calculate what should be the factors α (throttling) and β (breaking) to attain the desired speed, restricting them to the [0–1] range. Those limited α and β values are then reused in equation (10), but now to determine the actual speed V in that instant (in opposition to the original desired speed). Since α and β are limited to the range [0–1] (in this way modeling the actual limits of the engine and braking powers), the actual motorcycle speed will not always be equal to the desired one.

Although it is not necessary for the studies shown in this paper, in the solution of equation (10), we also consider additional controls on α and β to avoid loss of adhesion (in acceleration, braking and curves), and the occurrence of *wheelies* (in acceleration) and *stoppies* (in breaking).

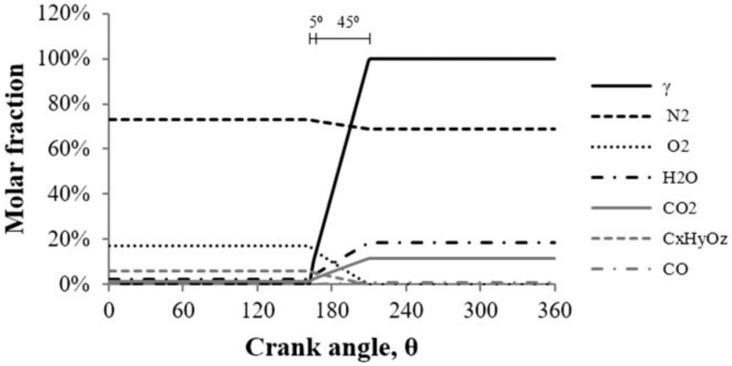

Figure 3. Variation of the molar fraction of components during the compression and expansion. In the end of the combustion, the molar fractions are: 0.689 N_2, 0.187 H_2O, 0.117 CO_2 and 0.007 CO.

With the determination of the evolution of α during the vehicle movement, it is possible now to calculate the vehicle energy expenditure during a time interval Δt using equation (11), where the α_i curve is calculated during the numerical solution of equation (10), $P_{max,eng}$ by equation (8) (considering $\alpha = 1$, and the engine r/min given by the speed V and the selected gear), and η_{eng} by equation (9).

$$e = \int_0^{\Delta t} \frac{\alpha_i P_{max,eng}(\omega_i)}{\eta_{eng}(\alpha_i, \omega_i)} \mathrm{d}t \tag{11}$$

The major simplifications in the models above described, compared to more sophisticated models present on commercial simulation programs can be summarized as: a known curve of extent of reaction, constant isentropic coefficients for expansion and compression, the hypothesis of homogenous mixture for each crank angle, and constant values for transmission efficiency, drag and rolling resistance coefficients.

Results and discussions

In this section, we will first analyze the behavior of the engine and the vehicle separately, and then perform a series of tests on the assembly. Figure 3 shows the variation of the composition of the mixture during the compression and expansion of the gases within the cylinder. It is observed that the combustion (controlled by the extent of reaction γ) starts at 20° before the top dead center (160°) and finishes 30° later (210°). For this specific engine r/min, the delay combustion takes 5° (value that varies with the engine r/min, since it is time constant). For all engine r/min, we considered that the main combustion always takes 45°.

In Figure 4, we see the evolution of pressure during compression and expansion. The dashed curve shows what would happen if the processes were

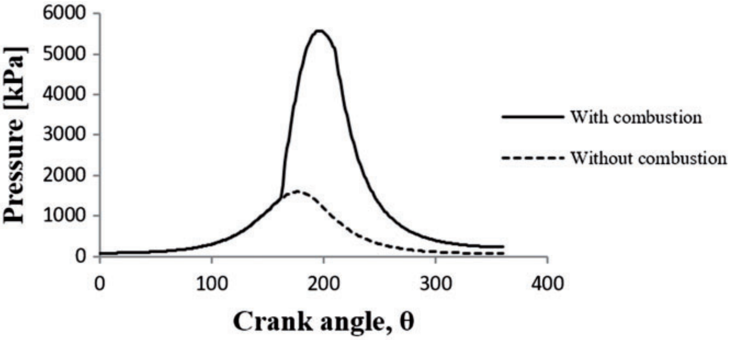

Figure 4. Pressure evolution during compression (0 to 180°) and expansion (180 to 360°).

isentropic and without combustion, in which case the gas would have the behavior of an ideal spring. The solid curve shows the "real" process, considering combustion, irreversibilities and heat transfer. Tian and Abraham[21] construct a qualitatively similar graph of the temperature evolution with and without combustion.

As explained in the last section, the curves calculated for one cycle (equation (7)) are integrated for each engine r/min, resulting in the engine power curve (equation (8)) and efficiency map (equation (9)). Figure 5 shows how power, torque and engine efficiency vary with engine r/min. Torque [N.m] is calculated dividing power [W] by the engine's rotational speed [rad/s]. Although in this case the power curve looks like a straight line, it is not. We show only the efficiency curve for $\alpha = 1$ (fully open throttle), but in the calculations, we obtain the entire map, $\eta_{eng}(\alpha, \omega)$. In respect to the quantitative behavior, Andrade,[25] using this model, arrived at a maximal error of 1.5 kW when comparing with the results of Bordonal and Souza[26] (experimental), Cunha[27] (empirical correlation) and Silva[28] (commercial package). Those comparisons demonstrate this simple model can be used as a first approximation.

Figure 6 shows the behavior of the motorcycle in a 400 m straight track. The solid line shows the desired speed evolution in case the rider wishes to accelerate from 0 to 60 km/h in 100 m, and then to maintain that speed until the end of the course. The 'v1-v2-v3' notation stands for v1: initial speed of the speed ramp, v2: final speed of the speed ramp, and v3: the cruising speed. In our case, the motorcycle is capable of accomplishing this desired evolution, so the real speed is the desired one. The dotted line shows the desired evolution in a 0–100–100 km/h event. The dashed lane shows the real behavior of the motorcycle in that case, in which the desired speed was not attained. The 'desired' curves are given, while the 'real' curves are calculated by the vehicle model, equation (10). We should stress that a 'desired' speed evolution is only given in a test track or in an empty road. In general, the 'desired speed' is function of the vehicle in front.

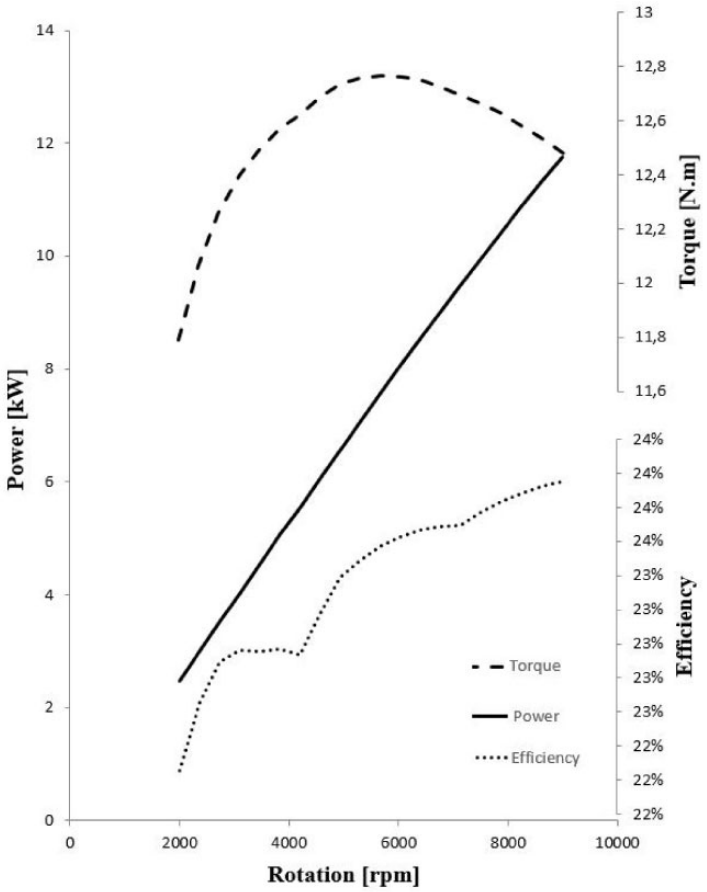

Figure 5. Power, torque and efficiency curves for full open throttle ($\alpha = 1$).

Figure 7 shows the evolution of the engine power, r/min and economy (in kilometers per liter) in each section of the track. The gear changes can be seen when the engine r/min abruptly changes. Also, interesting is the lower power demanded for the cruising section than for the acceleration section, notwithstanding the larger aerodynamic drag in the cruising section.

The transitions from Figures 3 to 7 cause a huge change of perspective for the students. Figures 3 and 4 present the behavior of the gases inside the cylinder for a given r/min. Figure 5 integrates those previous results for several r/min, showing now the behavior of the engine as a whole (power, torque and efficiency). Finally, Figures 6 and 7 exhibit the overall behavior of the motorcycle, implicitly considering what happens inside the cylinder for each crank angle (Figures 3 to 4), then the engine (Figure 5), and all the resistive forces around the vehicle (equation (10)).

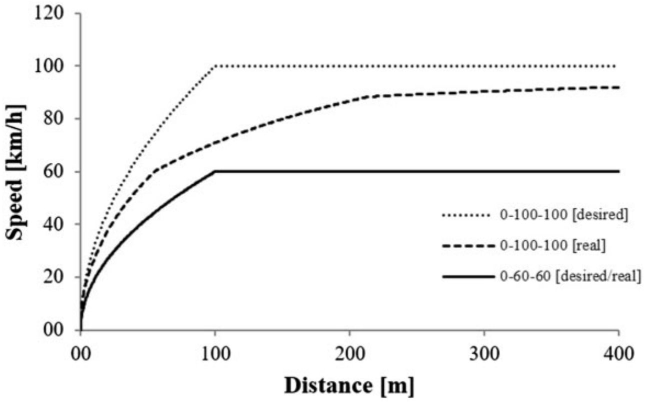

Figure 6. Motorcycle speed evolution in a 400 m track. The 'v1-v2-v3' notation stands for v1: initial speed of the speed ramp, v2: final speed of the speed ramp, and v3: the cruiser speed.

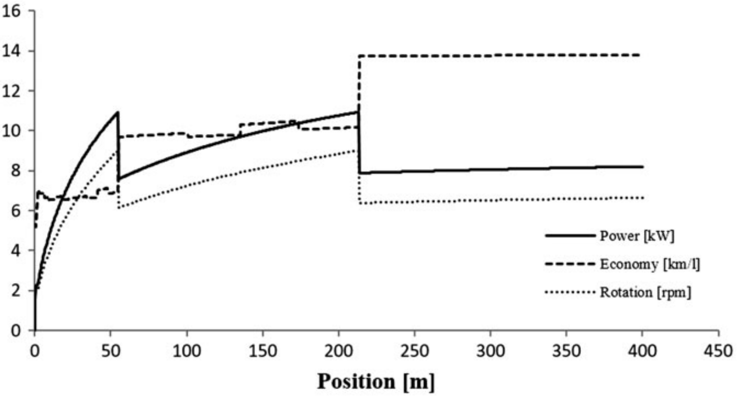

Figure 7. Power, rotation and economy.

Testing conditions

In this section, we are going to computationally test four engines: *real engine* (considering all the losses), *Otto engine* (based on the classic Otto Cycle idealizations, with no losses and instantaneous combustion), *perfect engine* (which converts all fuel energy into mechanical energy, akin to an electric engine), and *variable engine* (in which we can vary all parameters independently).

These engines will be installed on three motorcycles: *real motorcycle* (with all losses), *perfect motorcycle* (without any losses), and *variable motorcycle* (that allows changes to the parameters). For all motorcycles, the rider will be considered as having mass equal to 75 kg, so even the *perfect motorcycle* will have some

Table 1. Engines and motorcycles tested in the track.

Component	Name	Description
Engine	*Real*	16 HP, non-isentropic compression/expansion, heat losses, internal friction, finite time combustion, bellow 100% volumetric efficiency, compression ratio 1:9.3
	Otto	45 HP, isentropic compression/expansion, adiabatic, friction free, instantaneous combustion, unitary volumetric efficiency, compression ratio 1:9.3
	Perfect	82 HP, converts all the energy of the fuel into mechanical power
	Variable	parameters vary from case to case
Motorcycle	*Real*	$m = 210$ kg (motorcycle 135 kg, rider 75 kg), $k_A = 0.3$, $C_R = 0.02$
	Perfect	$m = 75$ kg (motorcycle 0 kg, rider 75 kg), $k_A = 0$, $C_R = 0$
	Variable	parameters vary from case to case

gravitational and inertial resistances. Table 1 summarizes these different models. As the engines have the same volumetric displacement, the power is larger for the engines with smaller resistances. That is the reason why, for example, the real engine has 16 HP and the ideal has 82 HP.

The standard track is 400 m long straight road, with the first 100 m being used to accelerate from 0 to 60 km/h (speed ramp), and the last 300 m ridden at the constant speed of 60 km/h (cruising speed). This test will be called 0–60–60 test. With this, we try to reproduce the urban traffic, with accelerations and cruises. The track has a slope of 1.15° ($\sin \varphi = 0.02$). We will evaluate two metrics during all the tests: the time to finish the track and the average fuel economy (kilometers per liter). First, we will evaluate the influence of the engine; then the influence of the motorcycle; and finally some special cases.

We start with some reference studies, shown in Table 2, without using the *variable* equipment for a while. All assemblies were able to run the track with the desired 0–60–60 speed evolution, taking 29.3 s. The economy varied from 16.8 km/l (*real engine real motorcycle* assembly) to 731.7 km/l (*perfect engine perfect motorcycle* assembly). It is interesting to note that the *real engine* installed in a *perfect motorcycle* (86.4 km/l) and the *perfect engine* installed in a *real motorcycle* (78.3 km/l) have relatively similar economies, indicating that both engine and motorcycle inefficiencies are important in the behavior of actual assemblies.

Effect of the engine

In this set of tests, we always use the *real motorcycle*, varying the parameters of the *variable engine*. All assemblies completed the 400 m track (0–60–60) in 29.3 s. The results are presented in Table 3 (the last three lines reproduce the results of Table 2). We can then see how the engine economy would increase if some losses were eliminated. Without heat transfer, the economy would increase by 89%,

Table 2. Economy for several engine/motorcycle assemblies in the 0–60–60 km/h test. All the tests use ethanol as fuel.

Engine	Motorcycle	Economy (km/l)	Difference (%)
Otto	*Real*	44.7	166
Otto	*Perfect*	290.0	1626
Perfect	*Real*	78.3	366
Perfect	*Perfect*	731.7	4255
Real	*Real*	16.8	reference
Real	*Perfect*	86.4	414

Table 3. Influence of the engine on the assembly behavior in the 0–60–60 km/h test.

Analysis	Economy (km/l)	Difference (%)
Variable engine (*real eng.* without heat losses)	31.8	89
Variable engine (*real eng.* without friction)	20.1	20
Variable engine (*real eng.*, isentropic efficiency 1.0)	19.7	17
Variable engine (*real eng.*, isentropic efficiency 0.8)	13.7	−18
Otto engine	44.7	166
Perfect engine	78.3	366
Real engine	16.8	reference

Note: In the real engine, the isentropic efficiency in the compression and expansion is 0.9. The real motorcycle is used in all the tests, with ethanol as fuel.

without the friction 20%, without the irreversibilities in compression/expansion the increase would be 17%.

Motorcycle's influence

In this set of tests, we installed the *real engine* in the *variable motorcycle* (which can be transformed in the other special motorcycles with the suitably chosen parameters). The results are shown in Table 4. All assemblies finished the 0–60–60 test in 29.3 s. The first two cases, 1–2, are limit cases, which had already been shown in Table 2. The other studies were carried out in two subsets. In the first, 3–12, we made some parameters null in order to determine the limit values of the phenomena. In the second subset, 13–24, we varied the parameters within practical ranges present in the market motorcycles. Comparing cases 4–6, we can isolate the importance of the motorcycle mass (if it was null we would have a 59% increase in economy), aerodynamic drag (if it was null the increase would be 50%) and rolling resistance (18%). Case 3 shows the influence of the slope of the track, which if it

Table 4. Influence of the motorcycle on the assembly behavior in the 0–60–60 km/h test.

Motorcycle	Case	Incline	Mass (kg0	k_A	C_R	Economy (km/l)	Difference (%)
Real	1	0.02	210	0.3	0.02	16.8	reference
Perfect	2	0.02	75	0	0	86.4	414
Variable	3	0	210	0.3	0.02	19.8	18
	4	0.02	75	0.3	0.02	26.7	59
	5	0.02	210	0	0.02	25.2	50
	6	0.02	210	0.3	0	19.8	18
	7	0.02	210	0	0	34.0	102
	8	0.02	75	0.3	0	29.5	76
	9	0.02	75	0	0.02	63.8	280
	10	0	210	0	0	54.8	226
	11	0	75	0.3	0	32.9	96
	12	0	75	0	0.02	86.4	414
Variable	13	0.01	210	0.3	0.02	18.2	8
	14	0.03	210	0.3	0.02	15.6	−7
	15	0.02	145	0.3	0.02	20.3	21
	16	0.02	275	0.3	0.02	14.4	−14
	17	0.02	210	0.15	0.02	20.0	19
	18	0.02	210	0.45	0.02	14.5	−14
	19	0.02	210	0.3	0.01	18.2	8
	20	0.02	210	0.3	0.03	15.6	−7
	21	0.0002	210	0.3	0.02	19.8	18
	22	0.02	210	0.3	0.02	26.6	58
	23	0.02	210	0.003	0.02	25.0	49
	24	0.02	210	0.3	0.0002	19.8	18

Note: The real engine is used in all the tests, with ethanol as fuel.

was horizontal would represent an increase of 18% in the overall economy. Cases 7–12 show combinations in which several parameters are made null simultaneously. For example, an ideal motorcycle on a horizontal track (12) would have a 414% increase in economy (86.4 km/l). In the second half of Table 4, we see the influence of the parameters within possible values for the current technology. Aerodynamics, for example, varies the economy in a range of −14 to +19%, cases 17–18. The use of a fully enclosed fairing, case 23, would increase the economy by 49%, although this change would have impacts on the total mass, motorcycle cost, and safety issues in side wind bursts. The mass of the motorcycle varies the economy in the range −14 to +21%, cases 15–16.

Special tests

Our models are quite general, enabling a great number of studies. In this subsection, we show some of the various possible special studies. During the classes, these special studies are not programmed in advance, but are born naturally from the students' questions. Some of them are solved right on the spot, some go wrong, needing some group discussion to discover the source of the error, and other studies require very large changes, which turn out to be themes for the course final projects.

In the first special study, the motorcycle travels the whole 400 m track in a constant speed of 60 km/h, no longer accelerating from 0 to 60 km/h in the first 100 m. In this way, we can study the influence of the constant reaccelerations common in urban traffic. The *real engine real motorcycle* assembly would have a mean economy of 22.0 km/l (31% increase over the 16.8 km/l).

Then we study the influence of the fuel, an important study in Brazil because, as the engines are *flex*, the riders can choose to fill the tank with ethanol or gasoline on the pump. Exchanging gasoline for ethanol, the *real engine real motorcycle* assembly would have a 62% increase in the economy.

In a third special study, we changed the desired speed evolution. Now the rider wants to increase the speed from 0 to 100 km/h in the first 100 m and then travel the last 300 m with a constant speed of 100 km/h. In Figure 3, we had shown the real behavior of the motorcycle, which in this case could not follow the desired speed. The *real engine real motorcycle* assembly finished the track in 20.7 s, reaching a top speed of 91.9 km/h, with an economy of 10.6 km/l. The *real engine perfect motorcycle* assembly would finish the track in 17.6 s, maximum speed 100 km/h, and economy of 47.2 km/l.

In the fourth special study, the motorcycle now uses 200 m to accelerate from 0 to 60 km/h (i.e. a smaller acceleration), and then maintains that speed in the last 200 m (a smaller cruising distance). The *real engine real motorcycle* assembly would have an economy of 18.0 km/l (7% increase over the 100 m acceleration), and the *real engine perfect motorcycle* assembly would be 95.9 km/l (11% increase).

A common modification to real motorcycles, performed by the riders themselves, is the change of the final drive transmission ratio. To analyze this, in the fifth special study, the desired test condition is an acceleration from 0 to 100 km/h in the first 100 m, and then a constant speed of 100 km/h in the last 300 m. The results are shown in Table 5, from which the students can reach two conclusions. First, increasing the maximum speed means less economy, case 4, because the bike faces a greater aerodynamic drag. It is interesting to note, however, that the highest maximum speed does not imply the shortest time of the track, case 1, since the evolution of the speed in the first 100 m of acceleration is also important to the total track time. This phenomenon is very common in races, in which sometimes, a vehicle is very fast on straight lines but slower than the others when exiting the curves.

The sixth special study is about the angle range of the main combustion (the last 90% of the reaction). For the 0–60–60 km/h test, the reference case (*real engine real motorcycle* assembly) with main combustion angle range of 45° resulted in an

Table 5. Influence of the ratio of the final drive in the in the 0–100–100 km/h test.

Ratio	Case	Front sprocket	Rear sprocket	Time	V_{max}	Economy (km/l)
3.38	1	13	44	20.22	96.0	10.23
2.85	2	13	37	20.72	91.9	10.64
2.77	3	13	36	20.77	92.2	10.61
2.57	4	14	36	20.96	97.7	10.16
2.33	5	15	35	20.60	94.0	10.54

Note: The real engine real motorcycle assembly is used in all the tests, with ethanol as fuel.

economy of 16.8 km/l, as already shown in Tables 2 to 4, If the main combustion would take 120°, the economy would decrease to 15.5 km/l.

The model presented in this paper is the most detailed model we use in the *Motorcycle Engineering* course before jumping to the use of commercial packages. The students, though, may use a finer detailing in their final project. For example, we could propose as further study the analysis of the initial mixture considering inlet and outlet pressure waves, swirls and tumbles.[29–33]

Conclusions

Michelangelo would have said that every block of stone has a statue inside it, which someone could interpret as meaning that a marble slab contains all the possible sculptures. That is true in a strict sense, but not in the wide one, as the beauty of the sculpture is found only in particular sculptures, not in the original slab. The same could be said about a detailed computational model, as if it would contain all the knowledge about a phenomenon. In a strict sense that is true, because it (allegedly) could foresee all the phenomena. In comparing simple models with commercial packages, one should bear in mind the following advantages of the former: open access to the mathematical model, easiness to learn the theory, range of phenomena studied (e.g. integrated engine and vehicle), gratuity, and flexibility to include new models. Commercial packages have advantages as well: better consideration of the physical phenomena, easiness of use due to user friendly graphical interfaces, and accuracy in the results. To draw attention to the basic physical phenomena is possible in both kinds of simulators, but in the commercial packages, this depends on a good tutorial or professor, while it is implicit in the simple model. Thus, notwithstanding this quantitative strength of detailed models, sometimes their complexities hide the real essence of the phenomena, the causal relations between the variables. Thus, we believe that simple models are not only didactic subsets of the more complex ones, but instead their very nakedness bears a kind of knowledge that cannot be found in the others. With this belief, we defend the use of simpler models side by side with more complex ones, in classes, research and in engineering praxis.

In this paper, we presented an integrated engine/motorcycle model in which we could freely modify its parameters both in the practical range and in the theoretical limits. The general model considered the finite time combustion, the varying composition depending on the chosen fuel, aerodynamic drag, gear shifting and other important phenomena. Four engines were tested (*real*, *Otto*, *perfect*, and *variable*), as well as three motorcycles (*real*, *perfect*, and *variable*). In the main set of studies (0–60–60 km/h, exchanging engines and motorcycles), the students learned that a *perfect engine* in a *real motorcycle*, or a *real engine* in a *perfect motorcycle*, would represent an increase in the order of 390% in the economy.

In the six special studies, the students learned how the losses in the engine can limit its ability to reach the desired speed, how ethanol is less volumetrically efficient than gasoline, that the reaccelerations are responsible for 31% of the motorcycle consumption, how the choice of sprockets influences maximal speed and minimal time, and the importance of the duration of the combustion.

Pedagogically, we strongly believe in the advantages of the combination of technical aspects (discussed in this paper) and general ones (e.g. culture, accidents, market) that are covered in our courses. In addition, we support the combination of subjects as Thermodynamics and Machine Dynamics; Technology Description and Mathematical Modeling; the integration of various systems, as engine, motorcycle, rider and traffic.

Seen as a group, our disciplines have a relatively deep range, as we integrate the undergraduate course (*Motorcycle Engineering*) with both graduate courses (*Studies on Bicycles and Motorcycles*, and *Propulsion of Bicycles and Motorcycles*). Unfortunately, we cannot promptly evaluate the success of those characteristics of our courses, but we have some positive signs, as the student enrollment, class participation, good blind evaluation of the professors made by the students, and a strong commitment of the students in the final projects. We believe this is partially caused by our method of integrating a general vision with more technical ones, but we also believe that a great characteristic of these two-wheeled courses is the motorcycle itself, always a passionate theme.

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