New engine concept development process: from green field to friction assessment for cam-roller follower valvetrain system, through an integrate engine design methodology

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where $\rho = 1.225 \text{ kg/m}^3$ air density; $C_x = 0.3$ drag coefficient or longitudinal aerodynamic force coefficient; $A_f = 2 \text{ m}^2$ transversal section of vehicle including wheels and parts under floor; $v_r$ is vehicle speed in m/s. Constant data used in (1) are for typical sedan car. Then aerodynamic torque at wheels $T_{aer}$ is evaluated with equation (2): 

$$T_{aer} = \frac{1}{2} \rho C_x A_f v_r^2 r_d$$

where $r_d = 0.28 \text{ m}$ radius of rolling defined as radius of rigid wheel that translate and rotate at same speed of pneumatic wheel. And in the end, aerodynamic power at wheels $P_{aer}$ is evaluated through equation (3) and plotted in Figure 62:

$$P_{aer} = \frac{1}{2} \rho C_x A_f v_r^3$$

Fig. 62: aerodynamic power versus vehicle speed
Figure 62 shows aerodynamic power and highlights growth trend at power of three of vehicle speed. Moreover, under 50% of vehicle speed range, aerodynamic power contribution is less than 20% of the maximum power.

About slope resistance, it could evaluate in the same way of aerodynamic resistance, through force, torque and then power. Slope force at wheels $F_{sl}$ is calculated with equation (4):

$$F_{sl} = m \ g \ \sin \alpha$$

where $m = 1400$ kg is full load vehicle mass in test condition or in according with SAE guide lines, vehicle mass in Standard C that means vehicle mass with all liquids with maximum load for vehicle, maximum number of passengers plus load per each passenger; $g = 9.81$ m/s$^2$, $\alpha$ is related to percentage slope $i$ in according to (5) and (6):

$$i = 100 \ \tan \alpha$$

$$\alpha = \tan^{-1}\left(\frac{i}{100}\right)$$

In this example, road slope is set at 4% that means every 100 meters along road steps 4 meters. Slope torque at wheels $T_{st}$ is evaluated through equation (7):

$$T_{st} = m \ g \ \sin \alpha \ r_d$$

And in the end, slope power at wheels $P_{st}$ is calculated by equation (8) and plotted in Figure 63:

$$P_{st} = m \ g \ \sin \alpha \ v_r$$
Figure 63 shows slope power versus vehicle speed and highlights linear relation between power and speed at constant slope.

Flat rolling resistance is mainly related to rolling coefficient $f$ as well as slope rolling resistance. $f$ increases with vehicle speed increase, in the beginning very slowly and then faster and faster, see Figure 64.

Figure 64: rolling coefficient $f$ trend versus vehicle speed. a) measure on radial and conventional tire; b) experimental curve – radial tire 5.20-14 inflated at 190kPa with 340 kN load – compared with equation (11)
Relationship $f(V)$ could be approximate with polynomial expression in form of (9):

(9) \[ f = \sum_{i=0}^{n} f_i v_r^i \]

In general, one considers two terms of equation (9) are enough to approximate in proper way experimental trend of $f(V)$, at last up to vehicle speed which rolling coefficient $f$ starts to rocket as highlighted in Figure 64. It could use follow equation:

(10) \[ f = f_0 + f_2 v_r \]

or

(11) \[ f = f_0 + f_2 v_r^2 \]

Equation (11) is usually preferred to (10) but in industrial application in case of unavailable data, one could use equation (12):

(12) \[ f = k_r \]

Equations (11) and (12) are plotted in Figure 65.
Figure 65 highlights rolling coefficient trend evaluated through (11) is strongly related with velocity at power of two. $f_0$ and $f_2$ values are evaluated experimentally tire per tire; for example in case of Figure 64b and in that test conditions, values are respectively $0.013$ and $6.5 \cdot 10^{-6} \text{ s}^2/\text{m}^2$. Velocity where $f(V)$ has knee, is tire critical velocity. Existence of tire critical velocity could easily explain through vibration phenomena happen at high speed. Flat rolling force at wheels $F_{rot}^{fl}$ according with equations (12) and (11) is evaluated respectively in equations (13) and (14):

\begin{align}
(13) \quad F_{rot}^{fl} &= m \cdot g \cdot k_r \\
(14) \quad F_{rot}^{fl} &= m \cdot g \cdot (f_0 + f_2 v^2_r)
\end{align}

where $k_r = 10^{-2} [-], f_0 = 9.5 \cdot 10^{-3} [-], f_2 = 5.6 \cdot 10^{-6} \frac{\text{s}^2}{\text{m}^2}$. In this case $m$ is vehicle mass in Standard E that mean vehicle mass with all liquids plus two passengers and load.
for each passenger. Flat rolling torque at wheels $T_{rot}^{fl}$ is calculated through equations (15) and (16):

(15) \[ T_{rot}^{fl} = m \ g \ k_r \ r_d \]

(16) \[ T_{rot}^{fl} = m \ g \ (f_0 + f_2 v_r^2) \ r_d \]

And in the end, flat rolling power at wheels $P_{rot}^{fl}$ is computed by equations (17) and (18) and plotted in Figure 66:

(17) \[ P_{rot}^{fl} = m \ g \ k_r \ v_r \]

(18) \[ P_{rot}^{fl} = m \ g \ (f_0 + f_2 v_r^2) \ v_r \]

Fig. 66: Flat rolling power resistance comparison with constant and speed related rolling coefficient
Under 40 km/h, constant rolling coefficient follow better experimental data respect to speed related one. But, as shown in Figure 66, flat rolling power resistance evaluated in both way gives pretty same result and for this reason equation (12) is preferred one. Otherwise, equation (12) is usable up to 70 km/h, or in others words up to error between equations (17) and (18) is acceptable.

In case of slope road, slope rolling resistance is evaluate as usual through force, torque and power. Slope rolling force at wheels $F_{rot}^{sl}$ is evaluated by equations (19) and (20):

\begin{align}
F_{rot}^{sl} &= m \, g \, k_r \, \cos \alpha \\
F_{rot}^{sl} &= m \, g \, (f_0 + f_z v_r^2) \, \cos \alpha
\end{align}

\(\alpha\) is computed in the same way as before and in particular with equations (5) and (6).

While slope rolling torque at wheels $T_{rot}^{sl}$ is calculated through equations (21) and (22):

\begin{align}
T_{rot}^{sl} &= m \, g \, k_r \, \cos \alpha \, r_d \\
T_{rot}^{sl} &= m \, g \, (f_0 + f_z v_r^2) \, \cos \alpha \, r_d
\end{align}

And finally, slope rolling power resistance $P_{rot}^{sl}$ is evaluated through equations (23) and (24) and plotted in Figure 67:

\begin{align}
P_{rot}^{sl} &= m \, g \, k_r \, \cos \alpha \, v_r \\
P_{rot}^{sl} &= m \, g \, (f_0 + f_z v_r^2) \, \cos \alpha \, v_r
\end{align}
Total power resistance $P_{tot}$ is sum of different contributions and in particular depends on flat, (26) or slope (27) road:

\begin{align}
(26) \quad P_{tot} &= P_{aer} + P_{rot}^{fl} \\
(27) \quad P_{tot} &= P_{aer} + P_{rot}^{st} + P_{si}
\end{align}

Figure 68 shows total power resistance for slope road at 4 %.
Usually for flat road, it is very important to determine characteristic speed of vehicle defined as vehicle velocity where aerodynamic resistance power equals rolling resistance power. Now, if power curve of IC engine is plotted in Figure 68, it intercepts total resistance power curve at certain point that shows maximum vehicle speed. Distance between total resistance curve and IC engine power curve is exuberant power and vehicle uses it to accelerate. At this point, one could verify acceleration that exuberant power can get to vehicle. In this way, target power curve of IC engine could verify and modified to achieve target SAE performance index of vehicle as defined through equation (28):

$$P.I. = \text{acc. 0 - 100} + \text{acc. 60 - 100 in IV} + \text{acc. 80 - 120 in V} + 1000 \text{ at } V_{\text{max}}$$

where: \text{acc. 0-100} is time in seconds to accelerate vehicle from 0 to 100 km/h; \text{acc. 60-100 in IV} is time in seconds to accelerate vehicle from 60 to 100 km/h in IV gear; \text{acc. 80-120 in V} is time in seconds to accelerate vehicle from 80 to 120 km/h in V gear; 1000
at $V_{max}$ is time in seconds to travel 1000 m at maximum vehicle speed. In particular vehicle performance index is used to link Customer Car Profile with Quality Profile in term of vehicle brilliancy.

First step to understand if IC engine has enough exuberant power or, in the other side, one could evaluate vehicle acceleration with present exuberant power, is calculate mass apparent sliding of vehicle $m_{as}$ in test conditions.

\begin{equation}
 m_{as} = m + \frac{J_{ICE} \tau_{ICE-whe}^{2}}{r_{d}^{2}} + \frac{J_{tra} \tau_{tra-whe}^{2}}{r_{d}^{2}} + \frac{J_{whe}}{r_{d}^{2}}
\end{equation}

where $m$ is vehicle mass in test conditions in Standard C for slope cases and Standard E for flat cases measured in [kg]; $J_{ICE}$ is IC engine inertia in [kg m²]; $\tau_{ICE-whe}$ transmission ratio between IC engine and wheels defined through equation (30); $J_{tra}$ is transmission inertia in [kg m²]; $\tau_{tra-whe}$ is transmission ratio between transmission and wheels in [-] defined by equation (31); $J_{whe}$ is wheels inertia [kg m²].

\begin{equation}
 \tau_{ICE-whe} = \frac{\omega_{ICE}}{\omega_{whe}}
\end{equation}

\begin{equation}
 \tau_{tra-whe} = \frac{\omega_{tra}}{\omega_{whe}}
\end{equation}

where $\omega_{ICE}$ is angular engine speed; $\omega_{tra}$ is angular speed of transmission; $\omega_{whe}$ is angular speed of wheels. Now, with apparent mass sliding $m_{as}$ could evaluate dynamic force at wheels $F_{dyn}$ through equation (32):

\begin{equation}
 F_{dyn} = m_{as} a
\end{equation}

where $a$ is vehicle acceleration in [m/s²]. Then, dynamic torque at wheels $T_{dyn}$ is evaluated through equation (33):
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(33) \[ T_{dyn} = m_{as} a r_d \]

And in the end, dynamic power at wheels is evaluated with equation (34):

(34) \[ P_{dyn} = m_{as} a v_r \]

Usually, this kind of analysis are carried on with commercial software as GT-Drive [87] that allow to study vehicle performance and vehicle – propulsion system matching. Basically, GT-Drive works in three different mode: static, kinematic and dynamic. In static mode, the solver creates a wide group of main performance index – power and torque, vehicle acceleration, … - on the whole engine speed range for every transmission rate; the engine load that the solver uses to calculate these index is defined by ‘static mode load factor’. In kinematic mode it is possible calculate the performance requirements and the emissions for cycles as NEDC; the vehicle speed is imposed and the solver calculates the engine performances. In dynamic mode is possible evaluate the transient performances – e.g. 0 – 100 km/h test –; the engine load is specified and the solver calculates the vehicle answer.

I-V Reference


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