CLASSIFIFICATION OF AGRICULTURAL TRACTORS ACCORDING TO THE ENERGY EFFICIENCIES OF THE ENGINE AND THE TRANSMISSION BASED ON OECD TESTS

J. Ortiz-Cañavate, J. Gil-Sierra, J. Casanova-Kindelán, V. Gil-Quirós

The authors are **J. Ortiz-Cañavate**, ASABE Member, Professor, **J. Gil-Sierra**, Professor, **J. Casanova-Kindelán**, Professor, and **V. Gil-Quirós**, Dr. engineer, Politechnic University of Madrid, Spain. **Corresponding author:** Jaime Ortiz-Cañavate. Universidad Politécnica de Madrid, E. T. S. I. Agrónomos, Dept. Ingeniería Rural, Avenida Complutense s/n, 28040 Madrid (Spain). Phone: 0034913365852. Fax: 0034913365845. E-mail: jaime.ortizcanavate@upm.es

Abstract. *A general goal of more energy efficiency encourages the use of tractors with better energy performance. Energy losses in agricultural tractors occur principally in the engine and secondarily in the transmission. In a previous article the authors proposed an efficiency index (c_{jt}) using some theoretical assumptions and applied it for two-hundred and fourteen models of tractors sold in Spain by mid 2006. In this article a new efficiency index (c_{kt}) that better represents the relationship between fuel consumption and available energy in the tractors was derived from official tests that follow the OECD codes. This index also considers the rolling resistance to establish the transmission coefficient, and includes tractors with CVT (continuous variable transmission) taking into account the specific characteristics of this transmission.*

Keywords. *Energy efficiency, Tractors, Engine, Transmission, CVT.*

The incoming energy in tractors is contained in the fuel which is injected into the engine. The drawbar pull, the power-take-off and the hydraulic power supplied to the implements are the energy outputs. The main energy losses occur in the engine because of thermodynamics, fluid dynamics and friction losses, as well as engine auxiliary loads. These energy losses are eventually dissipated as heat (Heywood, 1988). Lower, but also important losses, take place in the transmission.

In a previous article (Gil Sierra, et al. 2007) a classification of tractors based on their energy efficiency was made and an efficiency index c_{jt} was established for 214 models of tractors sold in Spain during the years 2005 and 2006. This index takes into account the points obtained by the OECD test codes, tested at the PTO and at the drawbar, but had some theoretical assumptions based on the work of Grisso et al. (2004) who developed an equation to fit the fuel consumption of a tractor at full throttle with variable loads measured during the PTO test:

$$Q\,(\mathrm{L/h}) = (a \times \mathrm{X} + b) \times \mathrm{P_{pto}}\ (\mathrm{kW}) \qquad [1]$$

where Q is the engine fuel consumption at partial load, X the ratio between the power at any partial load and at the rated power, P_{pto} the rated power at the PTO, and a and b are parameters.

The same authors extended the equation to evaluate the consumption at lower engine speeds:

$$Q\,(L/h) = (a \times X + b)\left[A \times X \times N_{red} + B \times N_{red}\right] \times P_{pto}\,(kW) \quad [2]$$

where N_{red} is the percentage of reduced engine speed for a partial load from full throttle (%) and A and B parameters.

There are multiple authors who have dealt with the energy efficiency of agricultural tractors, from whom we emphasize the following articles: Dyer and Desjardins (2003) studied the amount of greenhouse gas (CO_2) emissions that can be attributed to agricultural machinery by using computer simulation of farm power requirements, machine hours and fuel consumption. Kim et al. (2005) have found a clear improvement of agricultural tractor performance by using the data from 926 diesel tractors tested at the Nebraska Tractor Test Laboratory from 1959 through 2002. The performance analysis included the specific volumetric fuel consumption, specific power, traction coefficient, maximum torque rise, and sound level. Kutzbach (2000) stated that in the future, continuous variable, power-splitting hydrostatic transmissions with electronic control will lead to further increase in the productivity of agricultural tractors and simplify their operation. Ryu et al. (2003) found that the power transmission efficiency of a tractor drive train varied from 56% to 86% with a mean value of 72.5% during field tests. This indicates that a constant-power transmission efficiency model used for a power drive performance may not represent the actual variability. Souza et al. (1994) considered two functional relationships for the efficiency of tractors, one as a function of speed and torque and the other as a function of travel speed and drawbar pull. They stated that multiple parameter curves are adequate to analyze the overall tractor efficiency for a tractor operating under different gear conditions. Zoz et al. (2002) introduced the concept Power Delivery Efficiency to establish how much of the engine power is available at the drawbar.

With the general adoption in 2005 for OECD test code 2 of the new 6 points tested at the PTO (OECD Standard Code 2, 2008), it is possible to have better overall information of the fuel consumption of the tractor engine by a new formulation of the efficiency index c_{kt} which is obtained from official tests performed at test stations which follow the OECD codes and that represents better the relationship between tractor fuel consumption and available energy.

DEVELOPMENT OF THE C_J AND C_K INDEXES TO EVALUATE THE ENGINE EFFICIENCY OF TRACTORS

Tractor test reports according to the OECD test codes 1 and 2 give data of fuel consumption, power and engine speed for the following points: a) rated power and full throttle at partial loads, b) standardized power-take-off speed at full and partial loads and c) maximum power.

With this background and following Grisso et al. (2004), Gil Sierra et al. (2007) calculated the specific volumetric fuel consumption, SVFC, for four points inside the power – engine speed diagram for each tractor (points 6 to 9 in fig. 1) according to the equation:

$$SVFC = \frac{(a \cdot X + b) \cdot [-(A \cdot X \cdot N_{red} + B \cdot N_{red})] \cdot P_{pto}}{X \cdot P_{pto}} \qquad [3]$$

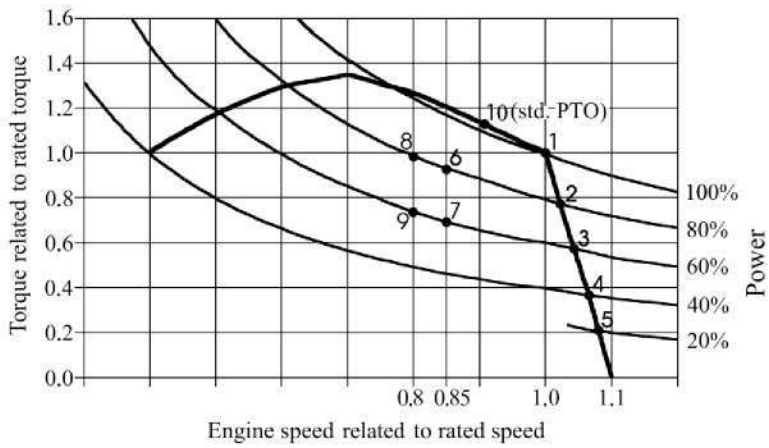

Fig. 1 - Points whose specific volumetric fuel consumption is employed to calculate the index c_j

where X, P_{pto}, N_{red}, a, b, A and B are the same as in [1] and [2].

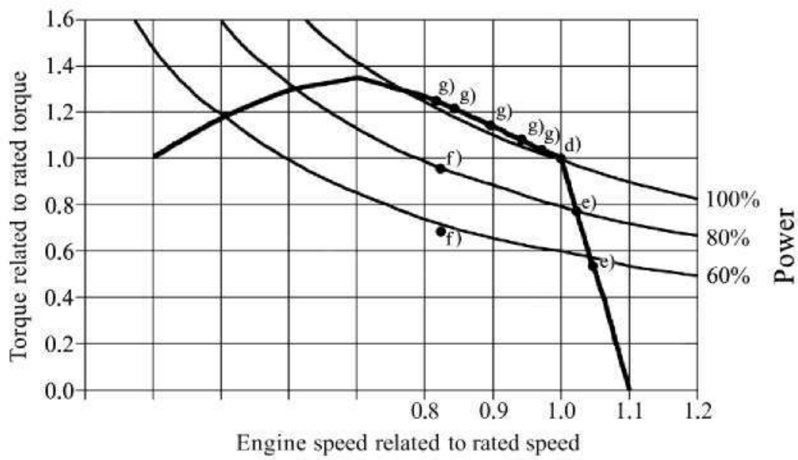

Fig. 2 - Points tested in the drawbar

In the drawbar pull test (fig. 2) the points tested are: point (d) at the rated power tested with the gear chosen by the manufacturer; 75% and 50% of that pull force (e); the same 75% and 50% of that force in another gear and at lower engine speed so that the travel speed is the same (f); the same d), e) and f) points with the gear that produces a travel speed close to 7.5 km/h and maximum power (g) obtained at several gear positions. Grisso et al. (2004) established that hourly fuel consumption during the PTO power tests and the drawbar power tests at rated points are identical, and that the varying PTO power fuel consumption data should apply to the drawbar load data and vice versa.

Because the coordinates of points (e) and (f) are power values close to 80% and 60% of rated power, and engine speed from near rated speed (points e) to 80% to 85% of rated speed (points f), equation [3] was used to calculate the specific volumetric fuel consumption (L/kW·h) for the four points 6 to 9 in that region of the diagram (fig. 1) (Gil-Sierra, et al. 2007).

Considering the 10 points of fig. 1, an index "c_j " of the energy efficiency of the tractor engine was defined, establishing double weight for the points 6 to 10 in relation to points 1 to 5, taking into account the normal operation of the engine of the tractor:

$$c_j = \frac{\sum_{i=1}^{5} SVFC_i + 2 \cdot \sum_{i=6}^{10} SVFC_i}{15} \qquad [4]$$

The weakness of this index is that points 6 to 9 are not directly measured in the test, and it does not take into account points at low engine speeds.

With the general adoption in March 2005 for OECD test code 2 of the 6 new points tested at the PTO (fig. 3), it is possible to have better overall information of the fuel consumption of the tractor engine. The 6 points are: 1) maximum power at rated speed; 2) 80 % power at rated speed; 3) 80 % power at 90% rated speed; 4) 40 % power at 90% rated speed; 5) 60 % power at 60% rated speed and 6) 40 % power at 60 % rated speed.

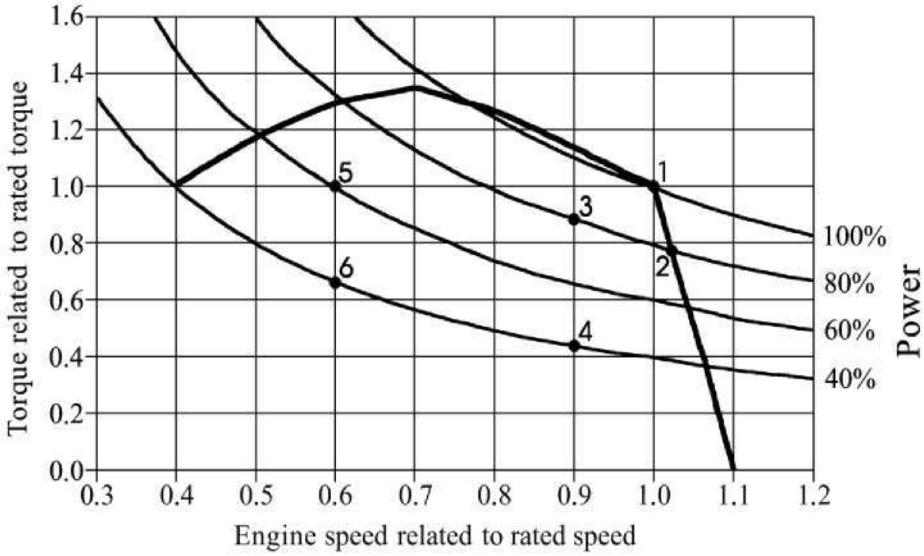

Fig. 3 – The six points tested at the power-take-off (OECD, 2005)

The index c_k is calculated as the average specific volumetric fuel consumptions of those six points:

$$c_k = \frac{\sum_{i=1}^{6} SVFC_i}{6} \qquad [5]$$

For tractors with diesel engines at a constant fuel delivery setting, the reported data of power measured in the PTO test are corrected to standard atmospheric conditions according to ISO Standard 15550, and consumption (L/h) is divided by corrected power to get the SVFC for each of the points considered.

Evaluation of tractors with CVT (Continuous Variable Transmission)

For tractors with CVT the indexes c_j and c_k are modified according to the special characteristics of this transmission. The efficiency of the CVT transmission is based not only on the mechanical and hydraulic losses produced from the engine to the wheels, but also on the capability of that transmission to locate the engine in the best operative conditions.

Tractors with CVT have electronic software to optimize the fuel consumption for each power and speed required for a specific task. The OECD test recognizes the specificity of these transmissions that can obtain in the automatic mode the minimum specific fuel consumption from the engine for each working condition (OECD Code 2, 2008). On the other hand, in the manual mode, the engine can rotate at the maximum speed given by points 1 to 5 of figure 1.

In the drawbar test carried out on these tractors, information is provided for two cases: 75 % and 50 % of pull at maximum power for the tests conducted in the automatic and in the manual modes, resulting in much lower specific fuel consumption for the first case than for the second.

The equation that gives the average reduction of the specific fuel consumption for the CVT transmission is:

$$RCVT = \frac{SVFC_{75auto}/SVFC_{75manual} + SVFC_{50auto}/SVFC_{50manual}}{2} < 1 \qquad [6]$$

The OECD drawbar pull test gives the specific volumetric fuel efficiency, which is 1/SVFC.

This value is used to calculate the index c_j for these tractors considering that the SVFC of points 1 to 5 in figure 1 have to be multiplied by this RCVT coefficient producing a lower (more efficient) value for c_j:

$$c_j = \frac{RCVT \cdot \sum_{i=1}^{5} SVFC_i + 2 \cdot \sum_{i=6}^{10} SVFC_i}{15} \qquad [7]$$

Also equation [5] is modified for c_k (fig. 3) in the same way, producing a lower value for c_k:

$$c_k = \frac{RCVT \cdot \sum_{i=1}^{2} SVFC_i + \sum_{i=3}^{6} SVFC_i}{6} \qquad [8]$$

EFFICIENCY INDEX C_{KT} TAKING INTO ACCOUNT THE TRANSMISSION

In order to consider the transmission efficiency, it is necessary to make use of the drawbar pull test (fig. 2), for points tested at rated engine speed (d) and maximum power at several gear positions (g) at engine speed lower than rated. At these points it is possible to know the power at the wheel axle by means of the equation (Ortiz-Cañavate, 2005, pp. 159-160):

$$P_{wa} = P_g + P_\rho + P_s = \frac{P_g + P_\rho}{1 - s} \qquad [9]$$

where P_{wa} the power at the wheel axle, P_g is the measured power in the drawbar test, P_ρ the power lost by rolling resistance, P_s the power lost by slip and s the slip(decimal).

The rolling or motion resistance ratio ρ is given by the equation (ASABE Standard D497.4, 2005):

$$\rho = \frac{1}{B_n} + 0.04 + \frac{0.5s}{\sqrt{B_n}} \qquad [10]$$

where B_n is a dimensionless ratio (= 80 for a hard soil).

The power lost by rolling resistance is equal to:

$$\mathrm{P}_\rho = W\rho v \qquad [11]$$

where W is the dynamic load on the traction wheels and v the travel speed.

In the PTO test it is possible to interpolate between the maximum power point, power at the standardized PTO speed and rated power to know the maximum power at the PTO when the engine runs at the same speed at each of the points (d) and (g) measured at the drawbar. Engine power can be estimated the same as PTO power because for most tractors, there is a minimal gearing between the engine and the PTO, and consequently minimum transmission losses occur between them. For each pair of power values at the wheel axle and at the PTO for the same engine speed it is possible to establish the transmission coefficient:

$$\eta = \frac{P_{wa}}{P_{pto}} \qquad [12]$$

where P_{pto} is the power obtained by the PTO test results interpolation.

In the previous article (Gil Sierra et al., 2007) a variable number of transmission coefficients η (usually 8 to 12) were calculated for each tractor and it was possible to differentiate between transmission coefficients for travel speeds slower than 8 km/h (η_{ls}) and coefficients for travel speeds faster than 8 km/h (η_{hs}). A statistical study was made by the Spanish Ministry of Agriculture (MAPA, 2006) to study the average percentage of time that a tractor works in each agricultural task. We grouped these tasks into three categories: tasks at the power-take-off, tasks at the drawbar with travel speed lower than 8 km/h and tasks at the drawbar with travel speed faster than 8 km/h. The value of the index c_j was split in three sections proportional to the percentage of the tractor time used at the power-take-off (c_j pto), at the drawbar at less than 8 km/h (c_j ls < 8 km/h) and at the drawbar at more than 8 km/h (c_j hs > 8 km/h) to calculate an efficiency index c_{jt} which takes into account the efficiency of the engine and the transmission coefficients:

$$c_{jt} = c_j pto + \frac{c_j ls}{\eta_{ls}} + \frac{c_j hs}{\eta_{hs}} \qquad [13]$$

Similarly this procedure allows also the calculation of the index c_{kt} taking into account the efficiency of the engine and the efficiency of the transmission. The ratios obtained for the above mentioned three tasks categories are close to 1/3 in all cases, and therefore a general equation for the index c_{kt} is established:

$$c_{kt} = \frac{c_k}{3}\left(1+\frac{1}{\eta_{ls}}+\frac{1}{\eta_{hs}}\right) \qquad [14]$$

Plotting the values of c_{kt} versus the rated power of every tractor, we fit an exponential regression line (fig. 4) that represents an average value of all tractors tested, meaning that approximately 50% of the tractors are above this line and 50% below.

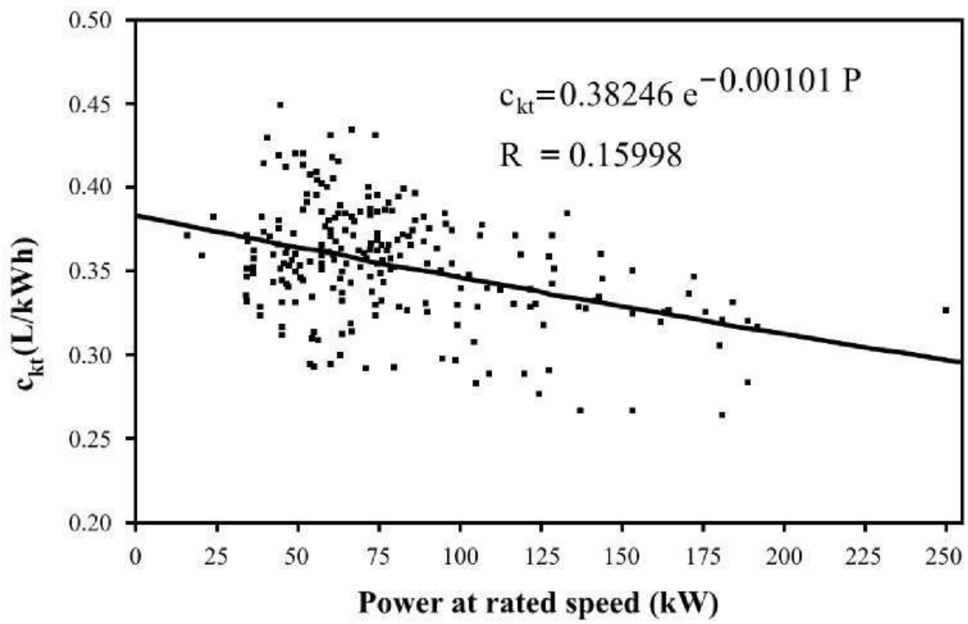

Fig. 4 – Efficiency index c_{kt} vs. power at rated speed for 249 models of tractors

To classify the data from the different tractor models a computer program was written in LabView language. The program asks for the data from the OECD test code related to power and consumption in the PTO and drawbar tests; it performs all the calculations to get efficiency index c_{kt}, and calculates the percentage of difference between the value of index c_{kt} and the average line for 249 models of tractors sold in the Spanish market by the end of 2007 and that were tested according to the OECD (fig. 4):

$$c_{kt} = 0.38246\ e^{-0.00101P} \qquad [15]$$

The tractor models were classified according to their index c_{kt} in seven categories with a bandwidth of 7% around the average line. A tractor which is represented by a point in one specific area belongs to that category. The seven categories are called from lower to higher values of c_{kt}: A, B, C, D, E, F, and G, "A" being the most efficient and "G" the least efficient (fig. 5). It is also useful to represent them with different colors, ranging from dark green through green, pale green, yellow, orange, pale red to red. (The CMYK coefficients of these seven colorations were defined in the previous article: Gil Sierra et al. 2007).

The results are shown as a histogram in figure 6 for the 249 tractor models considered. The number of tractors in each category is shown in each column. There are a smaller number of models in the most and least efficient categories, and a larger number in the middle categories. The tractor models classified according to this histogram follow a normal distribution. This is verified by the Kurtosis normality test where, for a 5% level of significance the value obtained is 0.2 (very close to 0) showing that that the distribution can be considered to be normal. Therefore it is justified to assume that this method chosen to classify agricultural tractors according to the energy efficiency of the engine and the transmission is satisfactory.

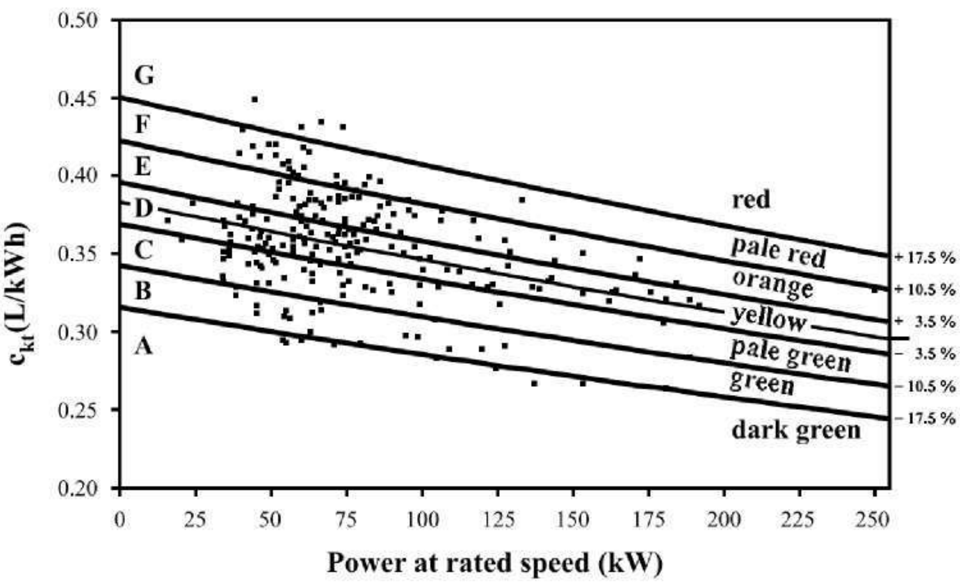

Fig. 5 - Areas in which the plot of points of index c_{kt} vs. rated power is divided

In the so-called "RENOVE Plan" to renew obsolete tractors in Spain, this index c_{kt} has been used since the beginning of 2007 by the Spanish Ministry of Agriculture to give financial support for the acquisition of new tractors of the most efficient categories. In the last OECD Tractor Codes Annual Meeting in Paris 2008 there has been also a proposal to adopt this index by other OECD countries.

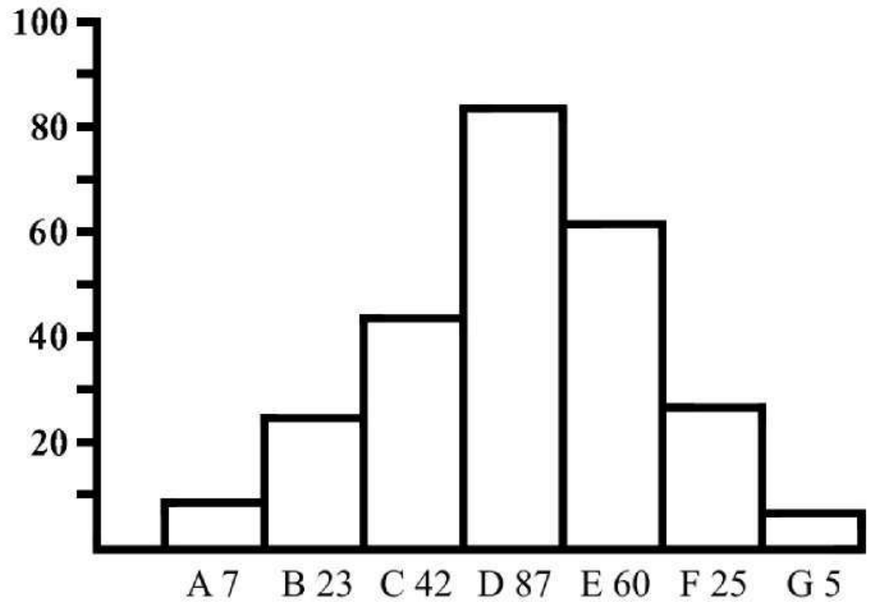

Fig. 6 - Histogram for 249 tractors in each category according to the efficiency index c_{kt}

The requirement of low exhaust pollutant gas emissions in the engine has some relationship with the fuel consumption. To take into account data coming only from low contaminant tractors, another plot of c_{kt} versus rated power has been made with the values of index c_{kt} for 120 tractor models sold in the Spanish market in 2008 with engines that fulfill the Tier 2 requirements. The exponential regression line of the index c_{kt} versus rated power for those 120 low pollutant emission tractors is:

$$c_{kt} = 0.38891\ e^{-0.000609\ P} \quad [16]$$

The classification published by the Spanish Ministry of Agriculture in its web page: (http://www.mapa.es/es/agricultura/pags/maquinariaagricola/renovacion.htm) takes into account the percentage difference between the c_{kt} value of each tractor model and the average regression line modified according to the models sold in the Spanish market every year and that have been tested by the OECD Code.

CONCLUSIONS

Two efficiency indexes are proposed to classify agricultural tractors according to their energy efficiency: c_k and c_{kt}, both derived from official OECD test codes. The index c_k is related only to the efficiency of the engine while the index c_{kt}

also takes into account also the efficiency of the transmission.

The efficiency index c_{kt} considers the rolling resistance to establish the transmission coefficient and is applicable to the continuous variable transmissions (CVT) by taking into account their specific characteristics.

A classification of agricultural tractors is established according to the value of their efficiency index c_{kt} placing each tractor in its corresponding energy efficiency category.

With the plot of c_{kt} versus rated power divided into seven areas with a bandwidth of 7% around the average line, the classification of the tractor models follows a normal distribution pattern. A computer program has been developed to calculate the efficiency index c_{kt} for each tractor and obtain its position in one of the seven proposed categories.

ACKNOWLEDGEMENTS

Authors wish to thank the Institute for Energy Diversification and Saving (IDAE), which is a public organization belonging to the Spanish Ministry of Industry, for its support.

REFERENCES

ASABE Standard D497.4, 2005. 52ª edition. Agricultural machinery management. St. Joseph, Mich.; ASABE.

Dyer, J. A. and R. L. Desjardins. 2003. Simulated Farm Fieldwork, Energy Consumption and Related Greenhouse Gas Emissions in Canada. Biosystems Engineering, 85(4), 503-513.

Gil Sierra, J., Ortiz-Cañavate, Gil-Quirós, V. and J. Casanova: 2007 Energy Efficiency in Agricultural Tractors. A Methodology for their Classification. Applied Engineering in Agriculture, 23(2), 145-150.

Grisso, R., M. F. Kocher, and D. H. Vaughan. 2004. Predicting tractor fuel consumption. Applied Engineering in Agriculture, 20(5), 553-561.

Heywood, J.B. 1988 "*Internal Combustion Engine Fundamentals*". New York, N.Y.: McGraw-Hill Inc.

Kim, K. U., L. L. Bashford and B. T. Sampson. 2005 Improvement of Tractor Performance. Applied Engineering in Agriculture, 21(6), 949-954.

Kutzbach, H. D. 2000. Trends in power and machinery. Journal of Agricultural Engineering Research, **76,** 237–247.

MAPA (Ministerio de Agricultura, Pesca y Alimentación). 2006. Distribución de las horas de funcionamiento anual del parque de tractores en España por gamas de potencia. http://www.marm.es/

OECD Standard Code for the official Testing of Agricultural and Forestry Tractor Performance. CODE 2. 2009.

http://www.oecd.org/

Ortiz-Cañavate, J. 2005 "*Tractores, Técnica y Seguridad*". Madrid, Spain: Mundi-Prensa.

Ryu, I. H., D. C. Kim and K. U. Kim. 2003. Power Efficiency Characteristics of a Tractor Drive Train. Transactions of the ASAE, 46(6), 1481-1486.

Souza, E. G., J. S. S. Lima and L. F. Milanez. 1994. Overall efficiency of tractor operating in the field. Applied Engineering in Agriculture, 10(6), 771-775.

Zoz, F. M., R. J. Turner and L. R. Shell. 2002. Power Delivery Efficiency: A Valid Measure of Belt and Tire Tractor Performance. Transactions of the ASAE, 45(3), 509-518.

NOMENCLATURE

B_n - dimensionless ratio for agricultural drive tires (ASABE Standard D497.4)

c_j , c_k – efficiency indexes of the engine (L/kW·h). Subscripts j and k refer to equations [4] and [5] respectively

c_{jt} , c_{kt} – efficiency indexes of the engine and the transmission (L/kW·h). Subscript t means that transmission is considered

N_{red} – percentage engine speed is reduced from full throttle (%)

P – rated power (kW)

P_g – maximum drawbar power measured in each tested gear position (kW)

P_{pto} – power at the PTO (kW)

P_s – power lost by slip (kW)

P_{wa} – power at the wheel axle corresponding to the maximum drawbar power measured in each tested gear position (kW)

P_ρ – power lost by rolling resistance (kW)

Q – volumetric fuel consumption (L/h)

s – slip (decimal)

$SVFC$ – specific volumetric fuel consumption (L/kW·h)

v – speed

W – dynamic load on the traction wheels (kN)

X – ratio between actual power and rated power (decimal)

ρ – rolling resistance ratio (decimal)

η – ratio between power in the wheel axle and power in the engine corresponding to the same engine speed (decimal)

η_{ls} – average value of η in each tractor measured at travel speeds lower than 8 km/h (decimal)

η_{hs} – average value of η in each tractor measured at travel speeds higher than 8 km/h (decimal)