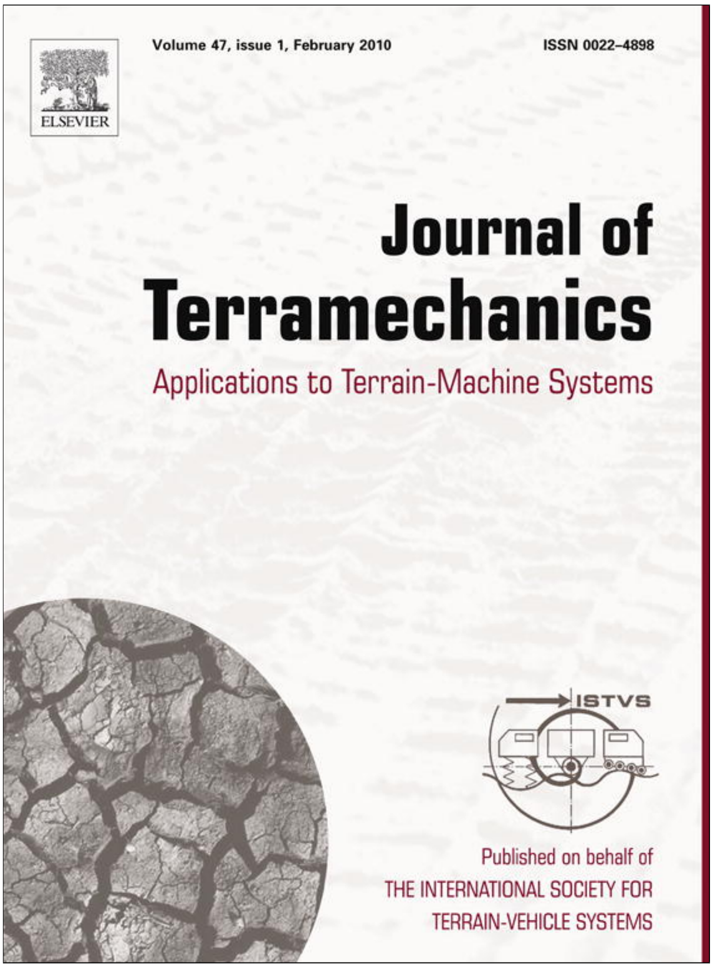
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Technical Note

Speed advice for power efficient drawbar work

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Abstract

Tractor manufacturers already offer engine – transmission control systems in which the operator decides whether low fuel consumption or high output is the priority and let a control system provide engine and transmission management. Less sophisticated tractors, as well as older equipment, still rely on the operator awareness upon what driving parameters most enhance efficiency. The objective of this study is to analyse the effect of driving parameters, namely forward speed and engine speed on the overall power efficiency. The overall power efficiency of a tractor performing drawbar work is the ratio between the output power at the drawbar and the energy equivalent of the fuel consumed per unity of time. Experimental data obtained from tractor field tests in real farm conditions, within the range of 0.2–0.4 for the vehicle traction ratio (ratio of the drawbar pull to the total weight of the tractor), show that increments of 10–20% on the overall power efficiency can be obtained by throttling down from 2200 min^{-1} to 1750 min^{-1} (idle speed). The reduction in ground speed and therefore in the work rate, may be overcome by shifting up the transmission ratio.

1. Introduction

The recent awareness of the negative effect of fossil energy in global climate changes has stimulated the efficient use of energy. Engineers must be aware of what values of efficiency are associated with each elementary process and make the right decisions towards the best possible overall energy balance. In agriculture, mechanization is the main concern since it makes use of fossil energy as it main source.

In draught operations, drawbar pull is set by the soil strength, type of implement, depth of operation and implement width. Tractor ground speed is limited between an insufficient working capacity for the assembly, and the level of comfort and safety of the operator. Being drawbar power externally imposed, the required engine power becomes dependent on the efficiency of the driveline and losses produced at the soil/wheel interface, with the latter influenced by soil surface conditions, tyre conditions (inflation pressure and wear) and axle vertical load. Finally the required engine power should be achieved by using the engine speed that meets both requirements of acceptable ground speed and engine efficiency.

In the past 10 years the main tractor manufacturers have been exploiting the full potential of intertwining the engine and transmission control systems for matching engine speed and load bringing to the market driving systems in which the operator has only to decide whether low fuel consumption or high output is the priority, and let a control system provide engine and transmission management. However less sophisticated tractors as well as older equipment, still in operation, rely on the operator awareness upon what driving parameters most enhance efficiency.

The overall power efficiency (η_{power}) of a tractor performing drawbar work is the ratio between the output

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Nomenclature

n	engine rotational speed, $\min^{-1}$	$\eta_{delivery}$	power delivery efficiency
v	tractor ground speed, $\mathrm{km\ h}^{-1}$	$\eta_{thermal}$	engine thermal efficiency
η_{power}	overall power efficiency	μ	vehicle traction ratio

power at the drawbar and the energy equivalent of the fuel consumed per unity of time. The η_{power} may be also represented in a dimensional form by the drawbar power per unity of the hourly fuel consumption ($\mathrm{kW\ h\ dm}^{-3}$). The objective of this study is to analyse the effect of driving parameters on the overall power efficiency, namely forward speed and engine speed, of a tractor operating over a range of field conditions found in primary and secondary tillage.

2. Literature review

Overall power efficiency of a tractor performing drawbar work may be expressed by the product of engine thermal efficiency and power delivery efficiency,

$$\eta_{power} = \eta_{thermal} \times \eta_{delivery} \quad (1)$$

where η_{power} is the overall power efficiency, $\eta_{delivery}$ is the power delivery efficiency, and $\eta_{thermal}$ is the engine thermal efficiency.

Power delivery efficiency of a tractor is the ratio of drawbar power over engine power [1]. Fig. 1 reproduces regression curves from tests in primary and secondary tillage [1], showing power delivery efficiency against the vehicle traction ratio defined as the ratio of the drawbar pull to the total weight of the tractor.

Engine thermal efficiency is the ratio of the output energy measured at the engine flywheel and the energy contained in the fuel consumed. Engine efficiency is usually represented by the inverse concept of engine specific fuel consumption ($\mathrm{g\ kW}^{-1}\ \mathrm{h}^{-1}$) available from tractor PTO tests (Fig. 2). Specific fuel consumption, and therefore engine thermal efficiency, varies with engine speed and torque, and consequently with power produced.

From Fig. 1, it is clear the dependence of $\eta_{delivery}$ on drawbar pull. The results in Fig. 2, reveal the dependence of $\eta_{thermal}$ on engine rotational speed and on engine load, ultimately influenced by the product of drawbar pull and tractor ground speed. Therefore a correlation of data concerning the overall power efficiency of a tractor performing drawbar work need always to consider drawbar pull, tractor ground speed and engine rotational speed as pertinent variables. A two-dimensional polynomial equation was put forward by Souza et al. [2] to evaluate the overall power efficiency of a tractor on concrete, relating η_{power} with ground speed and drawbar pull. As stated by the authors, the correlation coefficients are only valid for a particular transmission gear of the tractor used in the trials, which explains why the equation of correlation only includes two of the three pertinent variables above mentioned. The same methodology was used by Souza et al. [3] to find correlation coefficients for a tractor operating in four different gears in a no-tilled clay loam soil. Four sets of correlation coefficients were advanced, one for each gear, valid only for the conditions tested.

Field evidence was provided by Jenane et al. [4] with a front-wheel drive assist tractor in three soil conditions. The engine was operated at full throttle, and at two different gears, corresponding to typical ploughing speeds. The

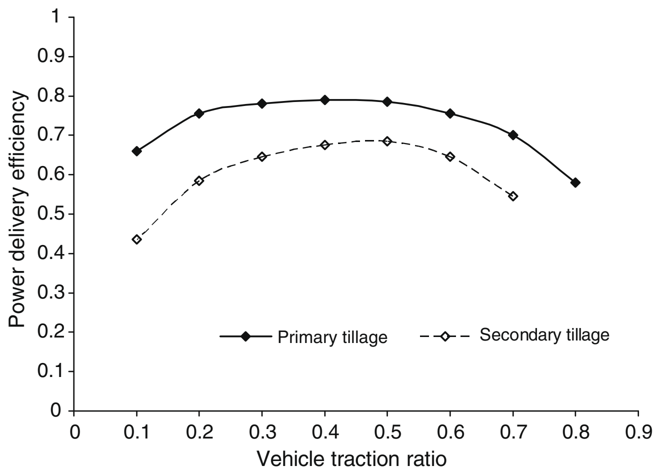

Fig. 1. Power delivery performance: comparison in primary and secondary tillage (Adapted from Zoz et al., 2002).

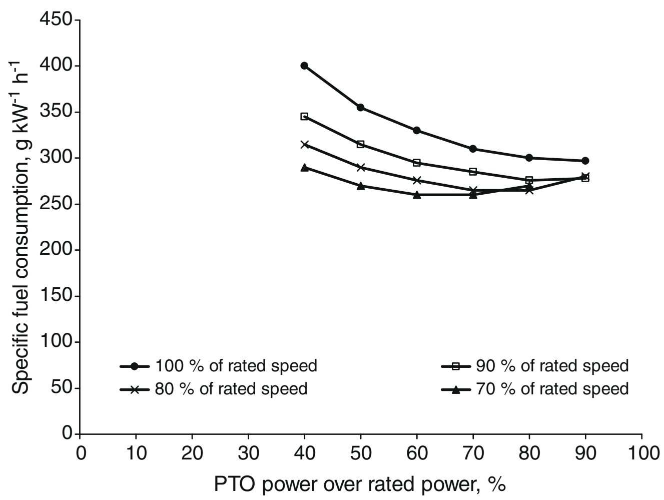

Fig. 2. Specific fuel consumption of a tractor engine from a PTO test (Serrano, 2002).

Table 1
Soil characteristics for the test sites: average properties of the soil for the 0–20 cm soil layer.

Site	Sand–loam–clay (%)	m.c.d.b. (%)	Bulk density (g cm^{-3})	Soil condition
Outeiro	55–23–22	7	1.351	Undisturbed sunflower stubble
Outeiro	55–23–22	5	1.408	Harrowed
Sítima	85–7–8	7	1.528	Harrowed
Louseiro-A	73–11–16	5	1.398	Harrowed
Sousa	63–12–25	11	1.284	Harrowed
Fitojardim	70–10–20	10	1.518	Undisturbed wheat stubble
Casao-A	65–14–21	8	1.456	Ploughed
Casao-A	65–14–21	11	1.533	Ploughed + harrowed
Louseiro-B	69–17–14	13	1.623	Undisturbed wheat stubble
Louseiro-B	69–17–14	13	1.427	Ploughed
Louseiro-B	69–17–14	12	1.592	Ploughed + harrowed

hourly fuel consumption per unity of drawbar power (dm^3 kW^{-1} h^{-1}), representing the inverse of η_{power}, was plotted against the vehicle traction ratio (μ). Results show values falling sharply from $\mu = 0.1$ to $\mu = 0.2$, then slowly to 0.3, becoming stable between $\mu = 0.3$ and $\mu = 0.5$. There is no clear distinction between results at different gears, meaning no clear evidence of η_{power} dependence on the ground speed.

Field tests tailored by Serrano [5] to obtain data on tractor and implement performance in particular dry farming conditions of southern Portugal, provide a source of data from which further evidence on the effect of driving parameters upon overall power efficiency can be driven.

3. Materials and methods

The tractor used in the field trials is equipped with a 59.7 kW (DIN) brake power engine, at 2200 min^{-1} rated speed; maximum torque of 280 Nm at 1400 min^{-1}. Within the main working range of 4–12 km h^{-1}, tractor transmis-

Table 2
Results from tractor tests in undisturbed soil.

Site	Test	μ	n idle (min^{-1})	Gear	n under load (min^{-1})	v (km h^{-1})	η_{power} (kW h dm^{-3})
Outeiro	1	0.23	1750	10Hi	1664	8.05	2.50
	2	0.23	2200	9Hi	2151	8.66	2.16
	1	0.29	1750	9Hi	1679	6.68	2.57
	2	0.28	2200	8Hi	2167	7.16	2.14
	1	0.30	1750	9Hi	1661	6.60	2.51
	2	0.30	2200	8Hi	2165	7.10	2.22
	1	0.36	1750	8Hi	1696	5.41	2.35
	2	0.36	2200	7Hi	2163	5.81	2.07
Fitojardim	1	0.27	1750	9-8Hi	1585	7.26	2.28
	2	0.29	2200	8Hi	2075	8.51	2.05
	3	0.27	2200	6Hi	2155	6.49	1.99
	1	0.29	1750	8Hi	1693	6.97	2.40
	2	0.28	2200	7Hi	2146	7.56	2.07
	3	0.28	2200	6Hi	2154	6.51	2.12
	1	0.32	1750	7Hi	1674	5.91	2.39
	2	0.32	2200	7Hi	2148	7.44	2.04
	3	0.32	2200	6Hi	2163	6.42	2.10
	1	0.35	1750	7Hi	1656	5.69	2.26
	2	0.34	2200	6Hi	2147	6.37	2.06
	3	0.32	2200	5Hi	2156	5.39	1.95
Louseiro b	1	0.28	1750	8Hi	1666	6.93	2.31
	2	0.29	2200	8Hi	2092	8.66	2.02
	3	0.28	2200	6Hi	2147	6.55	2.11
	1	0.32	1750	8Hi	1656	6.81	2.48
	2	0.32	2200	7Hi	2158	7.55	2.25
	3	0.29	2200	6Hi	2156	6.50	2.10
	1	0.32	1750	8Hi	1609	6.61	2.31
	2	0.34	2200	7Hi	2108	7.30	2.05
	3	0.35	2200	6Hi	2154	6.46	2.20
	1	0.36	1750	7Hi	1665	5.83	2.54
	2	0.36	2200	6Hi	2158	6.33	2.13
	3	0.35	2200	5Hi	2151	5.43	2.13

sion offers six gear options (5HI to 10HI) duplicated by clutchless engaged LO options, which provide 20% speed reduction in each gear. The tractor was operated in the four-wheel drive mode. Tyre dimensions are: 13.6R24 in the front and 16.9R34 in the rear. The tractor is factory equipped with a tractor-performance-monitor (*TPM*), monitoring engine speed, ground speed, slip and fuel consumption per hour. The information provided by the *TPM* is volatile; this limitation was overcome by the development of a portable computer based record system [6]. It records the signals from the tractor *TPM* sensors and also incorporates the information from a 50 kN load cell, measuring drawbar pull.

Soil characteristics and surface conditions are shown in Table 1.

Trailed type medium-weight offset disc harrows were used to apply drawbar pull. The range of values for drawbar pull was provided choosing between 20 or 24 discs and also by setting the angle between disc gangs at different values. Tractor was tested with front ballast weights mounted on the frontal three-point-linkage. The static weight distribution was 52% front and 48% rear, for a total static load of 52 kN. Inflation pressures were 100 kPa and 70 kPa for the front and rear tyres, respectively, adjusted to the static vertical load, according the tyre manufacturer manual.

Tractor was operated by a professional tractor driver, who was asked to perform three different tests, according to the selected transmission gear ratio and throttle position.

Test 1: throttle adjusted to a idle speed of 1750 min^{-1} (80% of the engine rated speed) and selecting the higher transmission ratio in which the operator was able to perform harrowing work, within his standards of comfort and safety and without engine overcharge (no significant decrease in engine speed under load).
Test 2: the same as in test 1, but adjusting the throttle to an idle speed of 2200 min^{-1} (100% of the engine rated speed).
Test 3: shifting down from test 2 so far as, according to tractor driver own judgment, the quality of the work and the work rate were still acceptable.

A set of runs resulted from the combination of tests 1–3 and imposed drawbar pull. In Outeiro; Sítima; Sousa; Louseiro-A test sites, each of the runs was performed along a 150 m strip of soil chosen randomly in the test site, replicated in the opposite direction to level off the effect of mild slopes. In Louseiro-B; Casao-A; Fitojardim test sites, each of the runs was performed along a 80 m strip of soil chosen randomly in the test site, and replicated four times,

Table 3
Results from tractor tests in harrowed soil.

Site	Test	μ	n idle (min^{-1})	Gear	n under load (min^{-1})	v (km h^{-1})	η_{power} (kW h dm^{-3})
Outeiro	1	0.27	1750	10Hi	1668	7.97	2.38
	2	0.26	2200	9Hi	2147	8.52	1.97
	1	0.30	1750	9Hi	1656	6.58	2.39
	2	0.30	2200	8Hi	2167	7.06	2.01
	1	0.31	1750	9Hi	1683	6.62	2.32
	2	0.31	2200	8Hi	2157	7.00	2.07
	1	0.39	1750	8Hi	1664	5.15	2.26
	2	0.39	2200	7Hi	2150	5.58	1.91
Sítima	1	0.28	1750	8Hi	1629	6.73	2.24
	2	0.27	2200	8Hi	1981	8.14	1.92
	1	0.32	1750	7Hi	1686	5.84	2.19
	2	0.32	2200	7Hi	2034	7.08	1.90
	1	0.33	1750	7Hi	1690	5.79	2.32
	2	0.34	2200	7Hi	2035	6.91	2.03
	1	0.36	1750	6Hi	1656	4.80	2.25
	2	0.39	2200	6Hi	2110	6.00	2.00
Louseiro a	1	0.25	1750	8Hi	1662	6.91	2.28
	2	0.27	2200	8Hi	2134	8.79	2.03
	1	0.31	1750	8Hi	1638	6.72	2.31
	2	0.32	2200	8Hi	1848	7.46	2.18
	1	0.33	1750	7Hi	1668	5.79	2.21
	2	0.34	2200	7Hi	1970	6.67	1.96
Sousa	1	0.25	1750	8Hi	1690	7.05	2.24
	2	0.28	2200	8Hi	1950	8.00	2.01
	1	0.30	1750	8Hi	1672	6.83	2.32
	2	0.31	2200	7Hi	2126	7.27	1.92
	1	0.31	1750	8-7Hi	1683	6.34	2.35
	2	0.33	2200	7Hi	2029	6.99	1.99

Table 4
Results from tractor tests in ploughed soil.

Site	Test	μ	n idle (min^{-1})	Gear	n under load (min^{-1})	v ($km\ h^{-1}$)	η_{power} ($kW\ h\ dm^{-3}$)
Casão	1	0.29	1750	7HI	1674	5.77	2.08
	2	0.29	2200	7HI	2120	7.29	1.91
	1	0.31	1750	7HI	1656	5.69	2.10
	2	0.32	2200	7HI	2075	7.04	1.79
	1	0.32	1750	6HI	1663	4.83	2.06
	2	0.33	2200	6HI	2143	6.16	1.84
	1	0.36	1750	6HI	1652	4.66	1.98
	2	0.37	2200	6HI	2057	5.78	1.87
Louseiro b	1	0.29	1750	7HI	1668	5.81	2.14
	2	0.30	2200	7-6HI	2109	6.63	1.68
	1	0.31	1750	7HI	1648	5.59	1.98
	2	0.31	2200	7HI	1939	6.58	1.74
	1	0.31	1750	6-7HI	1656	5.24	2.06
	2	0.31	2200	6HI	2155	6.25	1.69
	1	0.38	1750	6HI	1655	4.67	2.06
	2	0.36	2200	6HI	2061	5.77	1.65

two in each direction. The average value was considered the result. Drawbar power was obtained from the product of the measured values of drawbar pull and ground speed. From calculated drawbar power and the measured hourly fuel consumption, overall power efficiency (η_{power}) was obtained, represented by the drawbar power per unity of the hourly fuel consumption (kW h dm^{-3}).

4. Results and discussion

Tables 2–5 summarize the results, with data organized to enable an easier comparison among the gear-throttle tests. Taking test 2 as reference, test 1 is the result of keeping the same gear (or shifting one gear up) and throttling down; taking test 3 as reference, test 1 is the result of shifting one gear up (or two) and throttling down. Therefore, a comparison between these tests provide information of the effect on the overall power efficiency resulting from: no gear change; shifting up one gear; shifting up two gears and reducing, in all cases, throttle position from 2200 min^{-1} to 1750 min^{-1} (20.5% reduction). Results are shown in Fig. 3, for all sites and field conditions. It reveals three main clusters of results according to the action taken on the transmission ratio: a ground speed increment between 2% and 7%, when shifting up two gears; a reduction in ground speed varying from 5% to 10% when shifting up one gear; a reduction in the vicinity of the expected value of 20% when no gear change has been decided. Fig. 3 also reveals, throughout the variation range of ground speed that increments on the overall power efficiency in the range of 10–20% are common, irrespective of the shifting action taken in the transmission. This result reveals that throttling down was behind the increment in the overall power efficiency, stressing the importance of the reduction in engine speed.

Table 5
Results from tractor tests in ploughed + harrowed soil.

Site	Test	μ	n idle (min^{-1})	Gear	n under load (min^{-1})	v ($km\ h^{-1}$)	η_{power} ($kW\ h\ dm^{-3}$)
Asão	1	0.23	1750	7HI	1679	5.96	1.90
	2	0.25	2200	7HI	2155	7.54	1.67
	1	0.25	1750	7HI	1667	5.92	2.04
	2	0.26	2200	7HI	2151	7.52	1.77
	1	0.26	1750	7HI	1675	5.88	2.03
	2	0.26	2200	6HI	2158	6.39	1.66
	1	0.26	1750	7HI	1671	5.84	1.94
	2	0.27	2200	6HI	2157	6.43	1.68
Louseiro b	1	0.25	1750	7-8HI	1682	6.33	1.86
	2	0.25	2200	7HI	2151	7.46	1.69
	1	0.27	1750	7HI	1671	5.75	1.91
	2	0.26	2200	7HI	2146	7.40	1.74
	1	0.27	1750	7HI	1666	5.74	1.96
	2	0.28	2200	7HI	2151	7.37	1.69
	1	0.29	1750	6HI	1688	4.93	1.91
	2	0.29	2200	6HI	2151	6.32	1.87

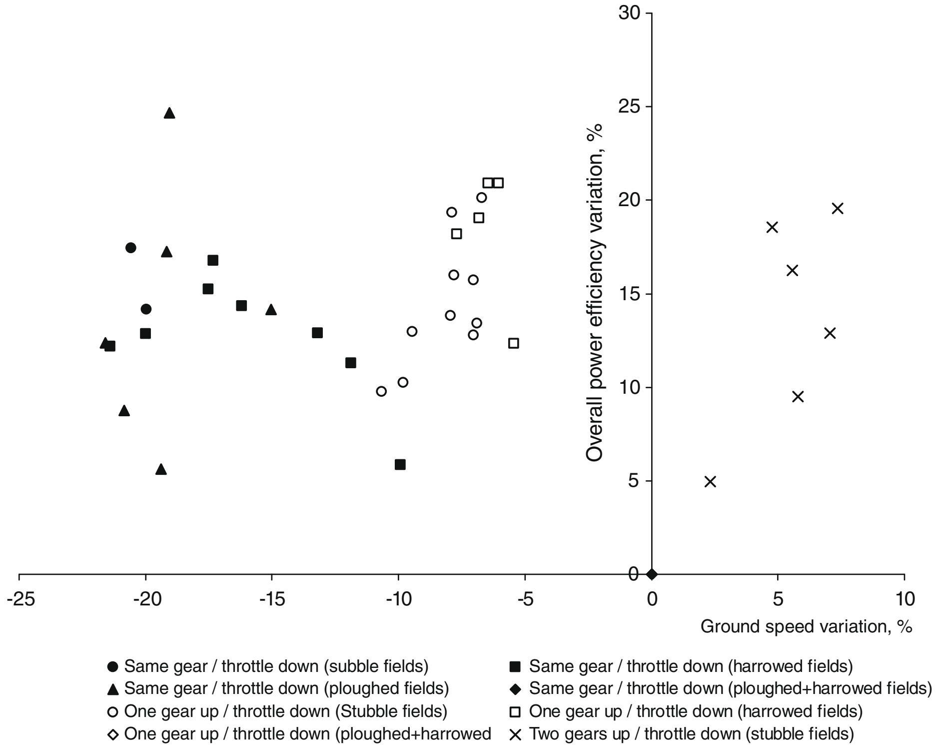

Fig. 3. Effect of gear throttle settings on the overall power efficiency of a tractor performing drawbar pull (priority on efficiency).

The increment in overall power efficiency (10–20%) put forward by Fig. 3, should be regarded valid for the range of vehicle traction ratio values of 0.2–0.4. Gains in the overall power efficiency induced by gearing up and throttling down should be less visible at higher values of vehicle traction ratio, and therefore at higher drawbar power. The reason can be driven from Fig. 2, where the advantage of reduced engine speed on engine thermal efficiency (and therefore on tractor overall power efficiency) is lost at higher values of engine power.

Taking test 3 as reference, test 2 is the result of keeping throttle and shifting up one or two gears. Fig. 4 reveals the expected consequence in the ground speed. At the same time, Fig. 4 shows that shifting up one or two gears, keeping throttle unchanged, produced a variation of overall power efficiency confined to ±8%. This small variation on overall power efficiency that resulted from shifting in the transmission (keeping throttle unchanged) is in line with other results that showed similar values for η_{power} at full throttle, in two different gear ratios [4].

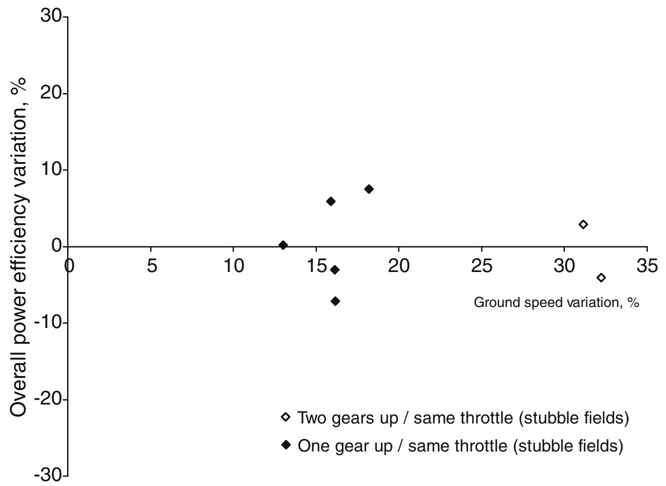

Fig. 4. Effect of gear throttle settings on the overall power efficiency of a tractor performing drawbar pull (priority on the work rate).

5. Conclusions

This work shows the importance of running tractor engine at speeds below the rated speed in order to enhance the overall power efficiency; throttling down from 2200 min^{-1} to 1750 min^{-1} (idle speed) lead to typical increments of 10–20%. These values should be regarded valid in the range of vehicle traction ratio (μ) of 0.2–0.4 since for higher values of μ the gains in the overall power efficiency are expected to be lower. The reduction in ground speed and therefore in the work rate, may be overcome by shifting up the transmission ratio. From an initial combination of selected gear ratio and throttle position, if an increment in the work rated is required, tractor operator should shift up through the transmission ratios, since only small variations on overall power efficiency are expected; the tractor driver should avoid to attain the same objective, by simply throttling up, as the result will be a deterioration on overall power efficiency.

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