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Design, Operation and Performance of a Gantry System: Experience in Arable Cropping

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The background to the development of a two-wheel drive agricultural gantry system, its assessment and evolution into a commercial machine are described. Details of the main frame, transmission, implement attachment linkages and vehicle control systems are discussed and their performance assessed. Soil and crop responses to gantry systems are presented.

A minimum power-to-weight ratio of 15 kW/t is recommended for adequate performance. To maintain vehicle stability, the ratio of the weight on the drive wheels to that on the undriven castor wheels should not exceed 75:25. Up to 70% tillage energy savings can be made by removing all traffic from the cultivated area and plough resistance may be reduced by up to 50%. Conventional traffic on the soil increases aggregate size and reduces porosity compared with zero traffic operations. The yield of spring barley in 1991 on a clay soil was increased by around 0·75 t/ha under zero compared with conventional traffic, confirming a similar winter wheat yield response in 1990.

It is concluded that suitably engineered gantries are able to carry out most operations on a farm and that they offer significant advantages over existing tractor systems in many aspects of their operation. The effect of improved boom stability on chemical applications needs to be quantified as well as the precise bout matching made possible by gantry systems.

1. Introduction

1.1. *Definition of a gantry system*

Probably one of the simplest definitions of a gantry is that given by Taylor in his paper[1] of 1991, namely "a framework supported at each end so that it spans a distance". In agriculture, the supports at each end are usually equipped with some means of locomotion to allow the gantry to traverse a soil bed. Steering along the bed is normally achieved by differential speed of the means of locomotion (i.e. wheels or tracks), which create a permanent pathway at a centre distance equal to the gantry's span. Movement out of the field, if it is needed, is usually in the longitudinal direction and is provided either by jacking down transport wheels or by turning the main drive wheels through 90 deg. and allowing them to be steered in a conventional manner. Spans from about 3 to 21 m have been recorded and are dependant upon crop requirements, practicality and cost.

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1.2. *Gantry research worldwide*

The history of gantries for agricultural use seems to have started with Alexander Halkett[2,3] in 1855. He produced a gantry mounted on rails which he saw as a means of applying steam power to all operations in agriculture. Henry Grafton, at a similar time, also put forward proposals, but his ideas centred around a tracked machine which only used rails to move it sideways along the headland. Little is then heard of gantries in the agricultural context for at least 100 years, but following that interlude, research on gantries has been widespread, both geographically and in the range of tasks which have been performed. In the former USSR, for example, the emphasis of research has been on the use of electrically powered gantries, both in the field[4,5] and in glasshouses,[6,7] but hydraulically driven machines have also been used for irrigation and chemicals application.[8] In Japan the accent has been on electric power and automation. Two systems, both on rails, have undertaken a wide

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range of tasks including robotic transplanting, soil tillage and puddling and harvesting.[9,10] At Hirosaki, an XY plotter type system has been used to locate the gantry[11] which moves on rails out of a purpose built building into the experimentally cropped area.

In the USA, use of off-peak electric power was proposed by Williams *et al.*[12] for their 30 m long gantry. Alcock and Jahns[13] used a centre pivot irrigator to position reference an electrically powered tool frame as did Wilton[14] in the UK who achieved unmanned operation and controlled traffic at normal speeds of boom movement. A very different approach was adopted by Carter *et al.*[15] in their 10 m span 268 kW four-wheel drive machine. The gantry was used for cotton and alfalfa production in field scale experiments and was equipped with purpose-built machines to fit under the frame by means of an implement latching system. This was one of the few experiments where zero traffic operation was maintained throughout the cropping sequence and for a number of years.

At Auburn in Alabama, Monroe and Burt[16] describe a 250 kW four-wheel drive machine commissioned for a wide range of research activities including tyre testing and harvesting, the latter with a plot combine raised on the gantry's high capacity linkage system. In Athens, Georgia, three Israeli-built gantries [field power units (FPU)] were evaluated in controlled traffic experiments.[17] The design of these 5·8 m span, 175 kW, 4wd machines originated from a Kibbutz in Israel where the commercial vehicles have now been leased back to them from the manufacturer. However, only with the cotton crop has a zero traffic system been maintained throughout the growing season. In Athens, the FPU's were being used for growing soybeans, sweet corn, wheat and sorghum. At Urbana in Illinois, a 12 m British commercial prototype gantry was purchased for use as a mobile instrumentation carrier to avoid disruption of the plant growth environment.[18] At the narrowest end of the gantry span, a 3 m machine was built at Clemson University (Saskatchewan) for tillage, bed shaping, planting, spraying and harvesting of vegetable crops.[19] A similar span machine with a mechanical differential speed drive system was built in the UK by Skurray (personal communication, 1993). This machine, which has 14 separate spray lines for the application of chemicals in plot trials, is capable of loading itself onto a small trailer for road transport.

In Australia, several farmers have built their own machines specifically for harvesting tomatoes and rockmelons.[20,21] Research at Gatton in Queensland[22] showed that controlled traffic operations could reduce crop establishment costs by 40% and their current research programme is using the commercial Dowler gantry described in this paper. This Australian work and trials in the UK[23,24] have shown that in the absence of wheel compaction, tillage energy savings of up to 55% can be achieved as well as significant improvements to soil tilth and structure. Crop establishment was also enhanced by zero traffic operations in certain conditions.[23] The Dowler gantry is also being used in the Netherlands for precision field operations controlled by a laser guidance system.[25] Two other interesting applications of the gantry can be found in the Netherlands, one within a shelf system of mushroom growing[26] which uses a lightweight gantry to level the surface of the beds and to harvest the crop while a 15 m wide unit is being used for the harvesting of gherkins.[27] Although this is still a labour intensive operation, use of a gantry ensures that there is the minimum of damage to the multi-pass harvested crop. The need to reduce crop damage in the field was one of the principal reasons for developing the 9 m vegetable harvesting gantry built at Silsoe[28] in the UK. This tracked vehicle design has been taken up by a number of commercial growers who have adapted it to act as a mobile packhouse for crops such as calabrese, greens and cauliflowers.[29] There are a number of other commercial machines which operate in this arena, but they are low power units acting purely as harvesting aids, some hydraulically driven others electric, and each proceeding at between 40 and 100 m/min and having no specific location for a driver.

Earlier gantry work at Silsoe concentrated on the protected crop in glasshouses and developed a system for growing and harvesting lettuce and for handling other produce.[30] More recently, an experimental gantry crane system was developed for dealing with outdoor container-grown nursery stock.[31] This battery-powered 8 m span machine increased workrate by 27% compared with manual handling, and with automation, has the potential to increase manual workrates by a factor of two.

It is evident from the foregoing that research and development of gantry systems has been extensive, particularly in the last two decades. The reasons for their introduction have included automation, boom stability, accurate position location, reduction of crop damage, minimization of land lost to wheelways, improved soil management and simply as an aid to research projects. It is also evident that few of the gantry research projects have been able to maintain completely traffic-free operation for all the crop production activities and that commercial use has generally been confined to the harvesting of high-value crops. For this reason, few data are available on crop yields from large areas of permanently non-trafficked soil.

1.3. *Objectives*

There were three main objectives of the work described here, namely (1) to develop an experimental gantry-based mechanization system capable of all operations, including harvesting, within a cereals-growing regime, (2) to measure soil and crop responses to its use and (3), to develop a commercial gantry capable of applying chemicals and of carrying out light cultivation and the sowing of crops. This paper describes the work associated with these objectives, but only the most recent results of soil and crop responses to the system are reported here.

2. Construction and development of the prototype vehicles

2.1. *Frame design*

The first vehicle was built in 1975 and was of a 1 m square section truss design spanning the 12 m gap between one driven and one castor wheel at each end. It was designed specifically to provide boom stability during spray and fertilizer application, accuracy of bout matching and minimum wheel traffic on the cropped area. Although the first prototype performed well in terms of control, mobility and boom stability, the square section frame made it difficult to locate heavy items, such as tanks and hoppers, in the ideal position for optimum weight distribution. If such items were placed above the frame, stability of the vehicle was impaired, while positioning on either side of the structure led to excessive loads being transmitted to either the castor or drive wheels. A second prototype (*Fig. 1*) overcame this problem by using a space frame with three principal members into which was built a demountable, commercially available, boom-type fertilizer spreader. When the spreader was demounted, the structural integrity of the frame was maintained by the introduction of a replaceable frame section. Although the overall structure was less stiff torsionally, twisting moments from ground undulations were practically eliminated by introducing, to the castor wheel mountings, parallel linkages which were restrained by hydraulic cylinders (*Fig. 2*). These identical cylinders were inter-connected and oil was allowed to pass freely between them. Rate of movement of the cylinders was limited by the 19 mm diameter pipe sizes, but these

Fig. 1. The second prototype 12 m gantry operating with a full width spring tine cultivator

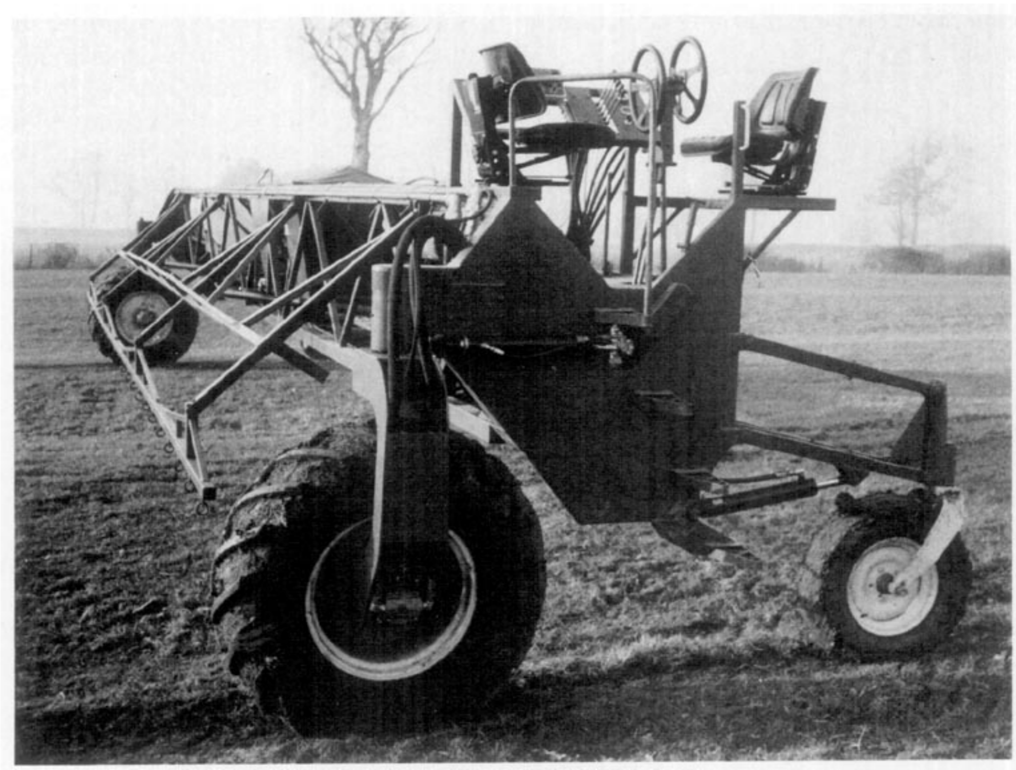

Fig. 2. Driving control position and drive and castor wheel arrangements on the second prototype gantry

were considered adequate for all but very abrupt changes in ground height. Because the engine end of the gantry was heavier, equal pressure in the cylinders only occurred following some twisting reaction within the frame. This problem of sagging at one end was overcome by introducing a supporting spring below the parallel linkage at the heavy end of the machine (*Fig. 2*, the spring was attached between the end of the cylinder rod and the bottom step) to react against the additional weight. A later alternative to this was to increase the load at the lighter end of the vehicle by forcing its parallel linkage down. This was achieved by introducing a double rather than a single acting cylinder, behind which air at about 800 kPa pressure was introduced. This had the advantages of simplicity and ease of adjustment for different loads and with a small air chamber of sufficient volume, provided near constant pressure operation.

2.2. *Power transmission and controls*

Both the initial and second prototypes had a commercial hydrostatic transmission which used independant pumps and motors for each of the two drive wheels. In this way, steering was provided by differential wheel speed, when the machine was operating at right angles to its span (*Fig. 1*) in the field. Forward and differential speed was controlled with mechanical linkages connected directly to the swash plates of the hydraulic pumps (*Fig. 2*). These linkages were actuated by a control column whose forward and reverse movement controlled forward and reverse speed, while a steering wheel at the top of the column introduced, through a chain and sprocket drive, speed differential between the two motors. A second steering wheel on a separate but parallel axis was geared 1:1 to the first steering wheel axle and hence automatically maintained the correct steering sense when the driver changed seats to drive in the opposite direction. For steering, when in road mode, each of the drive wheels could be turned by hydraulic cylinders through 120 deg. around a pivot mounted vertically above the wheel (*Fig. 2*). These were controlled by separate manually operated spool valves. High-speed motors drove the wheels through epicyclic reduction gears. A single speed range from 0 to 19 km/h was provided by the transmission. Additional hydraulic services were furnished by tandem gear pumps supplying individual motors. Unladen weight of the second prototype gantry was 3·75 t and motive power was from a 48 kW air-cooled engine providing a power-to-weight ratio of 12·3 kW/t. The driver was positioned at the engine

Fig. 3. The third prototype gantry with H-section linkages for raising and lowering implements

end of the vehicle over a line between the castor and drive wheels.

A third prototype vehicle, with a similar hydrostatic transmission, was developed over a period of years commencing in 1983 (*Fig. 3*). This was designed to carry out a wider range of tasks than hitherto, including both ploughing and the harvesting of cereal crops. The main differences between this vehicle and the other prototypes were its greater engine power (74 kW), the use of electrohydraulic controls for all functions, the introduction of a driver's cabin and the provision of three point linkages, one with a power take-off (p.t.o.) drive. Steering and forward/reverse speed control was through a steering wheel mounted on a slide similar to an aircraft joystick. Pushing the steering wheel forward from a central position increased speed, while turning the wheel when in field mode induced a differential in the speed of the wheel motors. Road mode steering was on four separate push buttons which controlled hydraulic cylinders acting directly on the drive wheels.

All of these and the most frequently used controls were mounted on a console attached to the driver's seat, the whole of which could be rotated through 270 deg. to accommodate different driving directions. Low-speed direct-drive wheel motors provided a torque of 13·2 kNm when operating at the maximum design pressure of 42 MPa and the unladen power-to-weight ratio was increased to 13·1 kW/t. As the two pumps were delivering exactly the same quantity of oil to each motor when in road mode, and coupling to three point linkage implements often required the drive wheels to be positioned at anything up to 90 deg. to each other, (the latter would mean that one wheel would need to be stationary while the other wheel rotated the vehicle around it), an additional valve was introduced. This opened up flow lines between the two pump circuits and allowed one wheel to rotate without the other or for the wheels to rotate at different speeds.

2.3. *Implement attachment linkages*

To mount implements across the full span of the gantries, parallel linkages were fitted beneath the main frame. Two different types of mounting were used, both of which provided for the mounting of four separate implements. One method used linkages and hydraulic cylinders at each end of every implement, while the other used single centrally mounted cylinders as shown in *Fig. 3*. The latter system consisted of four H-section frames whose top ends were mounted on a horizontal pivot along the bottom edge of the gantry frame. Double-acting hydraulic cylinders were pivoted from the gantry to the centre

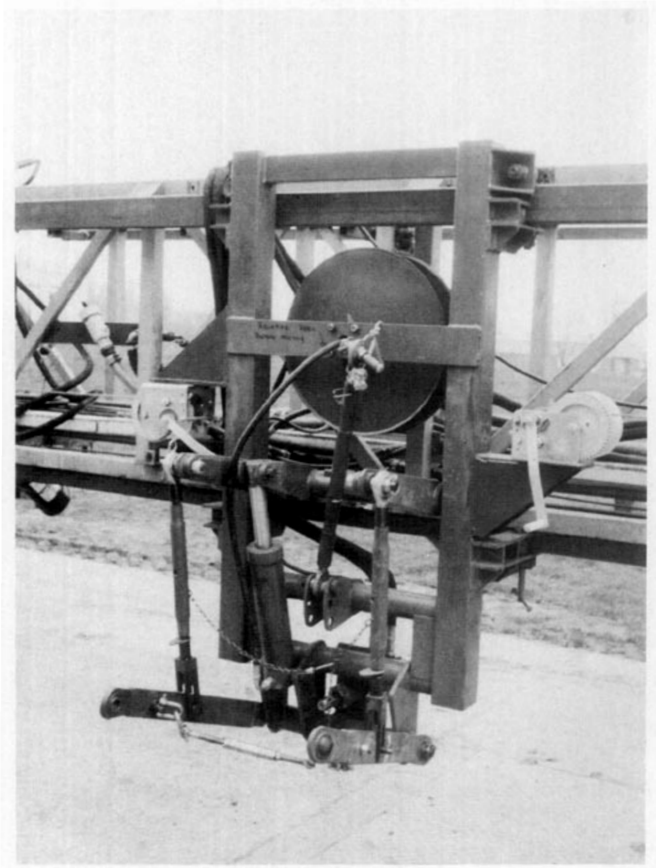

Fig. 4. Cross-slide three point linkage on which was moved by hand operated winches on the third prototype

of the H-sections and two additional adjustable length rods from the gantry to each implement made up a parallel linkage. Implements were attached to the lower end of these four points and the control system allowed each of the implements to be raised and lowered separately or as one unit. When used as one unit, all the lift cylinders were inter-connected and this allowed each of the implements to rise and fall in response to changes in ground contour across the gantry width.

The third prototype vehicle was also equipped with two standard three-point linkages on cross-slides (*Fig. 4*). These permitted the use of standard three-point linkage-mounted implements, usually on a part-width basis, two being necessary when ploughing for example, to allow the full torque from each wheel to be transmitted. The linkages had a lift capacity of about 30 kN at their ball ends and one was equipped with a hydraulically driven 30 kW p.t.o. and with auxiliary hydraulic tapping points. Hand-operated winches were used to index the units across the gantry frame.

2.4. *Implements*

A spring-tine cultivator and a set of rolls were designed to operate across the full width of the gantry using the under-frame linkages (*Fig. 3*). Each implement consisted of four separate frames of relatively light construction made possible by the multiple attachment points. The outer frames were shaped to allow the drive wheels to swivel from field to road mode, but were sufficiently distant from the castor wheels for them to operate unhindered. The smooth rolls, which were mounted on the H-section frames, were made light enough to be fully mounted but with ample strength to withstand the soil-firming forces which were applied to them hydraulically. Because each roll had to be operated by just one hydraulic cylinder and be allowed to pitch in all planes, a central mounting through a spherical bearing was used. This bearing was positioned as close to the soil surface as possible to minimize the pitch moments created by the horizontal draught force. On raising the rolls, they were maintained level by contact with the underside of the gantry frame. The self-weight of the units was about 100 kg/m width, and an additional 500 kg/m could be applied to them hydraulically using a constant pressure system regulated by a relief valve.

2.5. *Cereals harvester*

Development of a satisfactory experimental cereal harvesting system for the gantry was undertaken over a period of about 5 years. Initially, and to minimize the size, weight and complexity of equipment needed for harvesting, a 2 m wide grain stripping rotor[32] was mounted on the rails used for the three-point linkages. All the material separated by this rotor was conveyed beneath the gantry frame and elevated to a tank positioned on top of the main beam. Material was unloaded from this tank by gravity into the modified front elevator of a standard combine harvester for final separation. Additional rails for the tank and elevator enabled these and the stripping rotor to be positioned at any point along one-half of the gantry frame and the complete bed harvested by operating along it in both directions. To deal with the stripped straw left after harvesting, a standard 3·8 m wide combine harvester cutting table and a straw chopper were coupled and mounted on the gantry. The straw was fed directly from the table into the chopper and spread by deflectors. All the harvester and chopping units were driven hydraulically. Use of this system in 1989 proved arduous, even for the relatively small area (about 4 ha) on which the machine had to

Fig. 5. Gantry-mounted cereals harvester with a 3·8 m wide cutting table and rotary grain and straw separation

operate. Separation at the rotor was less efficient than anticipated, and a larger holding bin had to be introduced. The straw chopping system was slow but effective.

To improve the whole system, it was recognized that complete separation of the grain would be required on the gantry. To do this, the threshing and straw separation system developed by Metianu *et al.*[33] was introduced (*Fig. 5*). This system replaced conventional straw walkers with two additional drums and concaves immediately behind the main drum and concave. Although this broke up the straw considerably, it provided straw and grain separation with the minimum of complexity and component size. The grain was then elevated to a conventional grain cleaning shoe from which it dropped into a holding bin within the gantry frame. The harvester was used in barley, oats and wheat in 1990 and was a considerable improvement on the initial design. However, two problems remained; overloading of the cleaning shoe when the correct forward speed for the stripping rotor was maintained, and unthreshed heads being lost over the back of the cleaning shoe. The straw chopping system had also proved less satisfactory than in 1989. The main difficulty with the latter was caused by the cereal stems not falling onto the cross auger because they had no weight at their top ends. This led to bunching of the crop in front of the cutting table followed by a sudden surge of material through the system and into the chopper. To overcome these and the problems described above, and to speed up the overall harvesting operation, the stripping rotor was replaced by a conventional 3·8 m wide cutting table. A fan was also introduced to separate some of the lighter material before it reached the cleaning shoe, and a re-thresher was provided to deal with the unthreshed heads.

3. Assessment procedures

Performance of the gantries was assessed by both extensive use and observation on a 90 ha commercial arable farm in Warwickshire and by their inclusion in a replicated trial. The soil on the commercial farm was a boulder clay and the fields, which were on undulating land and irregularly shaped, ranged in size from 11 to 15 ha. Manoeuvrability of the gantry in two of these fields during chemical application to a growing crop was assessed by recording the time needed for headland turns. These were compared with measurements taken in the same situation on ten similar commercial farms using conventional tractor systems with wheels "as found". To determine crop losses, which are equivalent to about half the area lost[34,35] the width of the wheelways was also recorded on these farms by measuring the distance from crop row to crop row. Because it was apparent that the wheelways on the headland tended to be wider (due to the rear wheels of the tractor overcutting the front wheels), these widths were measured separately. Forward speed was determined from data recorded at random positions in the field.

If a gantry is viewed from one end, i.e. along its span, the design can be seen to be essentially similar to a conventional tractor, with a large, driven wheel separated from a smaller, non-driven wheel, by a distance equal to its wheel-base. However, unlike a tractor, this machine spends as much time travelling in "reverse" as it does in the more conventionally accepted forward direction. This by itself causes no problem, but the centre of gravity (c of g) of the gantry is higher than that of a tractor. Therefore, the addition of equipment or other loads which may alter the machine's stability adversely, could lead to the risk of overturning when decelerating rapidly in "reverse" (i.e. with the drive wheels leading). To determine the risk of this situation occurring, some assessments were made around the design of the second farm prototype.

The replicated trial, designed to study soil and cereal crop responses to zero and conventional traffic, was on an Evesham series clay soil[36,37] located at Silsoe (Table 1). The soil was loosened to 0·4 m depth in July 1986 with a rotary digger[38] equipped with subsoiling tines. In spring 1991 mole drains were drawn with a winch system at 2 m centres and 0·55 m depth across the site to intersect with the main drains installed on the headlands in 1981. Gantry and conventional traffic were compared from 1987 until the present, using tine cultivation and mouldboard ploughing as the means of primary cultivation on three replications of plots measuring 24 m wide by 35 m long. The tine cultivator consisted of heavy duty sprung legs with soil engaging 75 mm wide twisted shares designed to give some soil inversion. Harvesting on the gantry plots was with the specially designed harvester which allowed the 12 m wide beds of soil to remain traffic free for the duration of the experiment. Secondary cultivation was with both power driven and/or passive machines depending on conditions, and sowing of crops was with a mounted 4 m wide pneumatic drill. To compare the draught requirements of the primary cultivators on the trafficked and non-trafficked soil, they were mounted on a three point linkage dynamometer.[39] However, the gantry was also equipped with flow, pressure and temperature transducers in the hydrostatic drives from which the draught data could be derived. A flow transducer was fitted at each wheel, together with a temperature sensor, while pressure sensors were installed in both pressure and return lines at each wheel. These transducers, together with overall motor efficiency curves, allowed the following measures to be made:

$$\text{Hydraulic power, } P = pq/600, \text{ kW} \qquad (1)$$

where p is differential pressure, bar and q is oil flow, l/min.

$$\text{Motor speed, } S = q/d, \text{ rev/min} \qquad (2)$$

where d is motor displacement, 1.

$$\text{Motor torque, } M_t = 0{\cdot}159pd\eta, \text{ Nm} \qquad (3)$$

where η is motor efficiency.

$$\text{Tractive effort, } D = M_t/r, \text{ N} \qquad (4)$$

where r is loaded wheel radius, m.

All data from the transducers were either recorded directly on magnetic tape, or transmitted via a telemetry link to a stationary vehicle equipped with a data processing system.[40] Calibration tests on an axle dynamometer[41] showed that wheel torque on the gantry could be measured with this system to within ±1·5%.

Soil tilth was measured using two techniques. The first of these used samples taken from the ploughed soil on single adjacent gantry and tractor plots (1991) and from the top 75 mm of all replicates of these treatments in 1992. These were collected using the technique described by Watts and Dexter[42] and then air dried and sieved. The other technique for assessing

Table 1
Soil description and textural analysis of the replicated trial site

Soil: Typical calcareous pelosol of the Evesham Series (Hodge et al.)[36]
Taxonomy: Clayey, mixed, mesic aquic eutrochrept (USDA, 1975)[37]

Soil constituents	[% by weight (USDA classification)]
Clay	59·5
Silt	23·5
Sand (fine)	14·9
Sand (coarse)	2·1
Texture	Clay
Organic matter	5·4
Calcium carbonate	7·7
Lower plastic limit (soil water content, % dry basis)	47·3
pH	8·1

soil tilth used four photographs of the soil surface taken on each plot after crop sowing. The tilths shown on these photographs were then compared with photographs of surface tilths which had been assessed by dry sieving. The sievings for these "standard" photographs had determined the proportion of clods passing through different sieve sizes and their mean weight diameters (MWD). The MWD is defined as:

$$\mathrm{MWD} = \sum_{i=1}^{n} X_i W_i \tag{5}$$

where X_i is mid size of each sieve, W_i is the weight of the aggregates of that size as a proportion of the total sample weight and n is the number of size fractions.

Thus nine clod size assessments for each treatment were obtained by matching the tilths on the new photographs with those on the standards and a mean value for each treatment determined.

Crop yield (corrected to 15% dry matter) was measured on all plots from 3·8 m wide by 33 m long cuts taken with the gantry harvester.

4. Performance of the prototype gantries

4.1. *Vehicle characteristics*

The first two prototypes were used mainly for spray and fertilizer application on the 90 ha arable farm, the second machine having been in regular use for 10 years. Slopes of up 20% were safely traversed, and when working across slopes, the tendency of the machine to crab could be overcome by steering one or both drive wheels slightly up-slope, a feature not available on most conventional tractors. Table 2 shows the times required for a range of headland turns with the gantry, compared with the mean for similar turns made by tractors using a temporary tramline system within a growing crop. These show that the gantry was slightly slower on a 180 deg. turn with a 12 m boom, but significantly faster than tractor systems when a 24 m boom was used. This was almost certainly due to the greater moments of inertia of the wider unsupported booms on the tractor requiring the driver to proceed more slowly to prevent damage. The reversing turn of the gantry system, although slower, is generally used only during the first operation in a field when marking out of the wheelways is needed. Table 3 shows that the width between undamaged crop rows with the gantry system in the body of the field was slightly wider than with the tractor systems, but on the headland, the gantry wheelways were somewhat narrower. Of more significance in the comparison between gantry and tractor systems, in relation to the loss of land to wheelways, is the fact that tractor systems create two wheelways for a given implement span, whereas gantries create only one. Forward speed also varied between the tractor and gantry systems. Table 4 shows the differences in travel speeds when field working and this gives some

Table 3

Tractor and gantry uncropped wheelway widths measured on farms as specified in Table 2

Position in field	*Width of tractor or gantry wheelway (standard deviation), mm* — *Winter wheat*: *Tractor*	*Winter wheat*: *Gantry*	*Oilseed rape*: *Tractor*	*Oilseed rape*: *Gantry*
Body	554 (25)	596 (91)	476 (38)	576 (69)
Headland	844 (137)	434 (50)	nr* nr*	587 (101)

* nr, not recorded.

Table 2

The time required for 180 deg. headland turns made by tractor systems (mean of 10 farms) and a gantry system (1 farm) during chemical application. The headlands were at right angles to the main body of the field

The mean (standard deviation) of the time (s) required for turning with:				
12 m wide booms		*24 m wide booms*		*12 m wide boom using a reversing turn with the gantry*
Tractor	*Gantry*	*Tractor*	*Gantry*	
11·4 (2·24)	14·0 (1·60)	22·8 (2·15)	16·0 (0·77)	26·5 (2·05)

Table 4

Travel speeds for tractor (from 10 farms) and gantry (1 farm) systems during spray and fertilizer application with a 12 m boom

Type of travel	*Forward speed, km/h* — *Tractor*: Range	*Tractor*: Mean	*Gantry*
On the headland		7·0*	8·0*
In the body of the field:			
spraying	8·0–10·1	8·7	10·0
fertilizer application	8·0–13·4	10·5	13·0

* Calculated from turn times and distance travelled

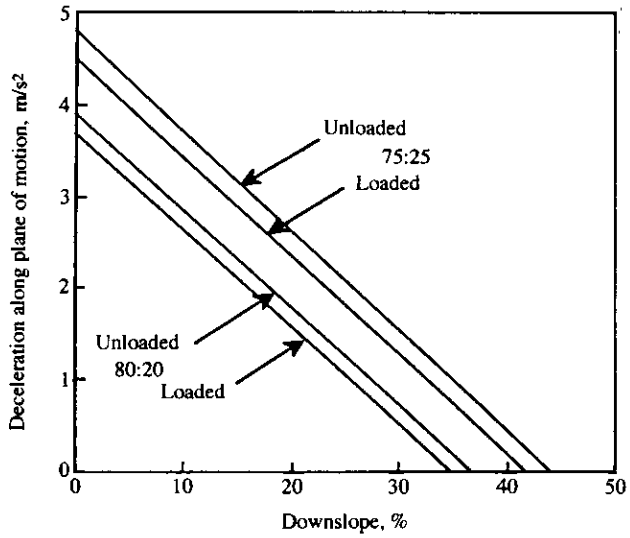

Fig. 6. Deceleration versus downhill slope for 80:20 and 75:25 drive to castor wheel load distribution. Limit of stability for loaded and unloaded condition of the second prototype gantry

indication of comparative work rates. A more detailed study of the latter was made during fertilizer application with a gantry[23] and suggested that gantry systems were likely at least to match tractor systems in their overall work rate.

The flotation feature of the full width implement system was essential in allowing each implement to maintain the same operating depth regardless of ground contour, which even over a 12 m width could be significant. The flexibility of independent control of each implement was also a considerable advantage because it allowed part-width operations in difficult conditions. Where the rolls were used, careful setting of the hydraulic pressure which could be imposed on them was necessary. If the pressure was too high there was insufficient weight on the drive wheels to provide the required traction.

Fig. 6 shows results of the calculations relating to the stability of a gantry which assumed that the castor wheels were on the point of lifting off the ground when stopping suddenly on a downward slope with the drive wheels leading. No friction or skidding were included in the assessment. As a guide, 3 m/s^2 deceleration is equivalent to stopping a vehicle from 10·8 km/h in 1·5 m or 1 s. The principal conclusion was that a change in the ratio of the mass on the driving wheels to the mass on the castor wheels from 75:25 to 80:20 would have a greater affect on stability than would a change from its unladen to its laden condition. For the machine in question, the 80:20 ratio could lead to an overturn.

Extensive use of the steering controls confirmed that the joystick design was ideal for field operation, allowing as it did, combined control of forward speed and steering. The push-button means of steering in road mode was less satisfactory when undertaking standard road manoeuvres but was useful when negotiating difficult turns which required each end of the gantry to be steered at a different angle.

4.2. *Soil responses*

Results reported in earlier papers by Chamen *et al.*[23,24] showed that, compared with conventional practice, cultivator draught and tillage energy were reduced by around 50% in a zero traffic regime. More recent results from the replicated field trial have continued to reveal the same significant overall reduction in energy requirement during seedbed preparation, but savings in draught during primary tillage have not always been apparent. In autumn 1990, for example, the specific plough draught recorded on the non-trafficked soil (Table 5) was higher than on the trafficked soil. This was considered to have been the result of an unusually low draught requirement on the trafficked plots caused by a very dry season following a dry autumn when considerable cultivation energy was expended. Watts and Dexter in their paper[42] looking at the changes in soil behaviour created by ploughing on these plots, identified significant differences in soil tilth. The MWD of clods produced by ploughing on the non-trafficked soil in 1990 was 17·3 mm compared with 24·5 mm on the trafficked soil. In autumn 1991, the MWD of the tilth on the zero traffic plots was 17·9 mm compared with 25·9 mm on the trafficked soil. However, measurements of the tilth following drilling of the crop using the photographic technique, indicated little difference between the treatments (Table 6). This is not

Table 5

Results of plough measurements on trafficked and non-trafficked clay soil

		Soil condition		
Year	*Measurement*	*Trafficked*	*Non-trafficked*	*SED**
1990	Depth of work, mm	159	135	17
	Specific draught, kN/m^2	46·2	62·1	6·2
1991	Depth of work, mm	201	197	1·4
	Specific draught, kN/m^2	125·1	72·4	4·8
1993	Depth of work, mm	191	207	3·5
	Specific draught, kN/m^2	134·8	85·5	0·7

* SED standard error of difference of means.

Table 6

Comparison of soil tilths on the trafficked and non-trafficked soils

Treatment	Mean weight diameter, mm	
	Photo, 1991	Sieving, 1992
Trafficked, plough	21·2	18·4
Non-trafficked, plough	20·7	16·7
Trafficked, tine	23·6	nr*
Non-trafficked, tine	18·6	nr*

* nr, not recorded.

Table 7

Results of tine cultivator measurements on trafficked and non-trafficked soil

Year	Measurement	Soil condition: Trafficked	Soil condition: Non-trafficked	SED*
1991	Depth of work, mm	124	114	4·9
	Draught per tine, kN	1·63	1·53	0·03
1993	Depth of work, mm	112	103	4·6
	Draught per tine, kN	1·88	2·48	0·07

* SED standard error of difference of means

necessarily conflicting evidence since the surface tilth can be quite different to the tilth from the top 75 mm of soil.

Where the tine cultivator was used for primary cultivation in 1991, there was no significant difference in draught between trafficked and non-trafficked soil (Table 7), but in this case the photographic assessments indicated that the tilth was finer on the gantry plots (Table 6). In 1993 the draught of the tines was significantly and substantially higher on the non-trafficked soil (Table 7), the reasons for which will be discussed later.

The management and maintenance of the wheelways are crucial to the operation of any controlled traffic system. On the commercial farm, the wheelways were never a problem despite their repeated use for about 15 years. At Silsoe, the wheelways within the plot experiment were subjected to numerous passes because of the part-width implements which were employed. The research gantry also weighed up to 8 t depending on its configuration and as a result around 10% of the wheelways became impassable during wet periods. This problem was also associated with specific areas within the field where drainage was historically poor despite the mole ploughing undertaken in 1991. Wheelways on the outside of the end plots, which only received half the number of passes, were never an obstacle despite some of them being in wet areas.

Table 8

Plant populations of spring barley and winter wheat (plants/m^2)

Traffic	Cultivation: Ploughed	Cultivation: Tined	Cultivation: Ploughed	Cultivation: Tined
	Spring barley, 1991		Winter wheat, 1992/1993	
Gantry	236	234	236/202	234/196
Tractor	167	181	167/221	181/146
SED*	17		17/47·2	

* SED standard error of differences of means.

4.3. *Crop responses*

Analysis of the number of spring barley plants established in 1991 following autumn cultivation showed that the trafficked plots had a significantly lower population (Table 8). This was attributed to the better seedbed conditions on the zero traffic plots and reflected earlier results with spring oats,[23] which although unharvested due to machinery problems, established a substantially higher population. Table 8 also shows the midwinter populations of winter wheat sown in autumn 1991, which overall were again significantly greater on the non-trafficked plots. The differences in spring barley populations in 1991 were reflected in the yield, which was significantly greater (at the 5% level) on the zero compared with the conventional traffic plots (Table 9). (The reason for the rather low yields was the need to carry out mole ploughing on the site following sowing of the crop.) These data confirmed the 1989 winter wheat yield results[23] which indicated that the gantry treatments resulted in 6·77 t/ha compared with the trafficked

Table 9

Yield (t/ha) of spring barley in 1991

Traffic	Cultivation: Ploughed	Cultivation: Tined
Gantry	5·51	5·53
Tractor	4·90	4·62
SED*	0·28	

* SED standard error of differences of means.

yields of 5·72 t/ha. In 1992 the harvest was so delayed by poor weather that shedding losses from the crop rendered the yield measurements unusable.

5. Development of a commercial gantry

A commercial version of these gantries was designed primarily for spray and fertilizer application, secondary cultivation and sowing (*Fig.* 7). All electrohydraulic controls were used, many of which were supported by logic and relay circuits on a printed circuit board. This allowed a "coordinated" steering system to be incorporated, which together with rotary potentiometers on the drive wheels to detect steer angle, enabled road mode steering to be accomplished through the steering wheel. It was also possible with this system to have an adjustable delay in the steering of the rear wheel, which was needed to counteract the tendency for the rear of the machine to move outside its line of travel with initial steer. Non-coordinated steering was provided in the form of front wheel steer only or independent steer of front and rear wheels. An air conditioned driver's cabin had all electrical controls accessed from a seat which could be manually rotated through 270 deg.

To improve the driver's view of key components and to make the machine visually more attractive, the original space frame designs of the main spanning beam were replaced by a hexagonal section tube made from folded steel sheet of 3 mm thickness. This hexagon, of 350 mm side length, contained all pipes and wires and joined, via monocoque end units and height adjustment slides, the engine and spray tank pods (*Fig.* 7). Ground clearance beneath the beam was adjustable from 800 to 1500 mm and separate means of height adjustment was provided for the 24 m wide spray boom. Space within the newly designed driver's cabin was limited by the beam height adjustment pillars on the one side and the need to minimize overhang beyond the wheels on the other (to avoid hedges, trees, fences etc. when making the headland pass around a field). Transport width of the vehicle was fixed by the 2·5 m wheel centres of the drive and castor wheels. Three linkage points on each side of the beam were designed to lift 0·5 t at their ends. Implements were attached to them through a parallel linkage system using the outer link ends on one side and the inner ends on the other. This left the other arms free for further implement attachment, for example the spray boom, and allowed for the simultaneous operation of two implements. Each pair

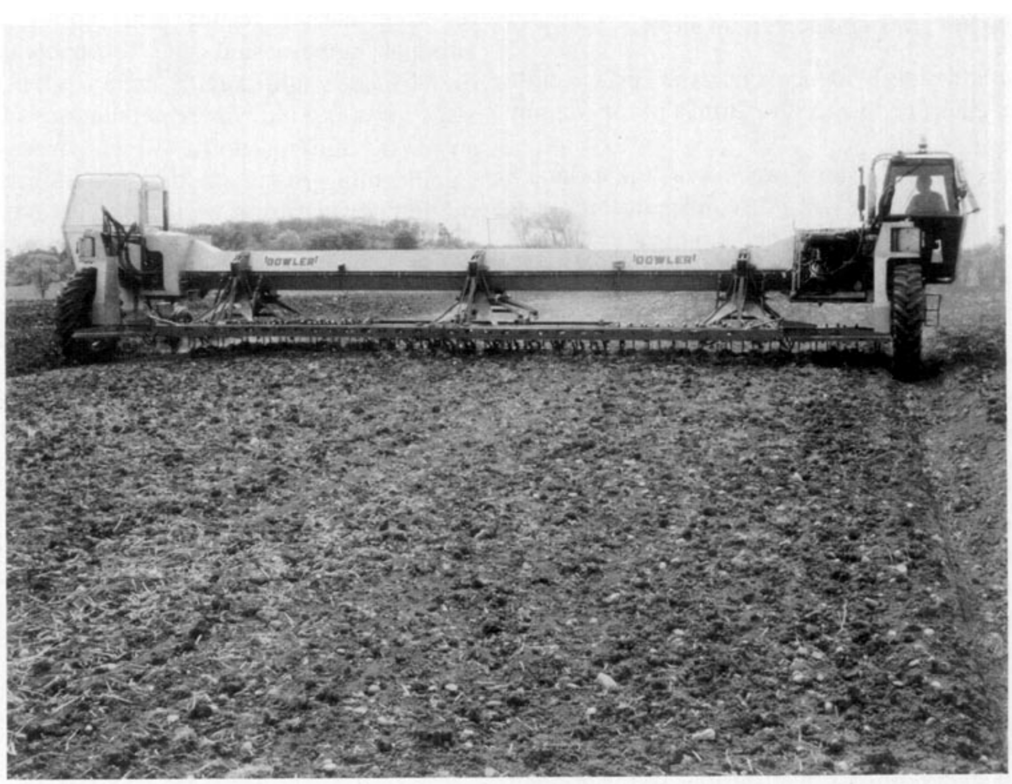

Fig. 7. The 12 m, 67 kW production gantry operating with three spring tine cultivator units

of linkages could be controlled independently and one or other of the pair isolated manually. A float selection switch allowed the implements to follow ground contours or to maintain a fixed height. A later addition to the production machine was a cross-slide three-point linkage and 30 kW p.t.o. This was attached to two rails on a framework slung beneath the main beam and was designed to operate over just half the span of the gantry.

To preserve the high level of cleanliness required for the hydrostatic transmission, it was provided with its own oil reservoir, while the services oil, which was used only to supply gear pumps, was contained in a separate tank integral with the cab end unit. A 67 kW engine provided an unladen power to weight ratio of 12·8 kW/t. The unladen vehicle weight at 5·5 t was considered high and means of reducing this will be sought. Of the unladen weight 62% of the vehicle was on the drive wheels when in road mode.

Weight distribution in field mode provided good stability with only about 70% of the weight on the drive wheels, but some penalty for this was paid by the higher loads on the smaller castor wheels, a factor which is discussed below.

6. Discussion

6.1. *Aspects of vehicle design and performance*

Two-wheel drive gantries with undriven castor wheels have a considerable advantage over four-wheel drive machines in their steering control and mobility. With four-wheel drive gantries only pre-determined steering manoeuvres are possible without sophisticated control systems which would be needed to achieve the flexibility inherently available with the two-wheel drive gantries.

The steering control system of any vehicle of this nature is crucial to its success, not only for manoeuvring between fields but for steering a straight course within a field. For headland turning, the ideal was found to be the combined controls offered by the joy-stick arrangement, but separate means of speed and directional control could be an advantage for road use.

These two-wheel drive gantries in field mode were slightly easier to steer with the drive wheels leading. This, in most cases, was almost certainly due to the greater rolling resistance of the smaller more highly inflated castor wheels, which tended to sink more without the pre-compaction of the drive wheels, particularly on the first pass across a field. The ideal would be to have an adjustable wheelbase, with a narrow setting for road use (when stability due to longitudinal deceleration is not a problem because the centre of gravity is a long way from either end and relatively low compared with the wheelbase) and a wider setting when in field mode. A four-wheel drive gantry would not suffer from the same problem due to the different weight distribution. The steering stability of the vehicle when operating with only part-width high-draught implements, e.g. with a plough positioned at one end of the gantry beam, was not a problem provided that sufficient torque and traction were available at the wheel required to do most of the work. Even if a constant 10% differential in wheel slip existed between one end of the gantry and the other, the driver had no difficulty with vehicle control; it would simply mean that the steering wheel would be turned slightly to the left or right.

The electrical feedback and proportional control system for road mode steering were essential for the commercial machine, but were found to consume excessive power leading to oil over-heating. This was overcome by reducing the system operating pressure when the vehicle was on the move, when much lower forces were needed to steer the wheels. A further improvement in this mode of steering would be a control system which ensured that the rear wheels followed in exactly the same path as the front wheels. A desk top study confirmed that measurement of the control parameters needed to achieve this would be possible, but the additional cost could not be justified for small production numbers.

The optimum span for a gantry has often been debated and the authors conclude that there is no one size that would suit all farming enterprises. On an arable farm for example, a large span would be ideal to minimize land lost to wheelways, but the cost of the harvester would increase dramatically and if travel distances between fields and farmstead were significant, transport speeds could be compromised. Spans of between 6 and 8 m are likely to be ideal for this type of farm, whereas smaller spans may be preferable in root or vegetable growing enterprises where bulky and heavy produce needs to be transported. Because different spans of machine can easily be constructed, optimization for a given farm can readily be accommodated.

Due to the larger structure of a gantry compared with a tractor, the unladen weight of these vehicles tends to be higher and this has been identified as an area where further improvements in the design could be made. The power-to-weight ratios quoted for the gantries described here (around 13 kW/t) are low compared with other vehicles designed for draught and applciations work. Conventional tractors tend to have a ratio of around 15 kW/t, and their largely mechanical transmissions are of the order of 10% more efficient than the hydrostatic transmissions used on these gantries.[43] It could be argued, therefore, that a hydrostatically driven gantry designed as a replacement for a tractor should have at least a 10% higher power-to-weight ratio than a tractor. However, the lower forces associated with draught implements used within a complete gantry system (see Section 4.2) would negate the need for this level of power and it is considered that a power-to-weight ratio similar to conventional practice would be adequate.

It is anticipated that gantries could increase cultivation work rates not only as a result of lower draught forces, but as a result of precise bout matching. With conventional tillage machines, markers are seldom used and yet observation suggests that with widths over about 4 m, considerable inaccuracy in matching the line of work can occur. An error of 0·5 m with a 6-m wide implement would not be uncommon, and represents a loss in work rate of 8%.

6.2. *Soil and crop responses*

In general, our experiences with zero traffic systems over the last 10–20 years have shown that removing all wheel traffic from the soil has a dramatic improving effect on its structure and tilth characteristics and a reduction in its strength. However, the reasons for the increase in draught and strength of the topsoil on the zero traffic tine cultivated plots are not clear (Table 6), although some confirmation of soil strength differences in the top 100 mm of soil are provided by cone resistance measurements (Table 10). These were taken 3 months before cultivation when the soil was at field capacity. One possible explanation relates to observed differences in the manner in which the differently treated soils fail during tine cultivation. On the tractor plots, the compacted soil fractures extensively on either side of the tines as a result of cracks being propagated around large aggregates. On the non-trafficked soil, these large aggregates are generally absent and soil failure occurs only locally around the tines. As a result, a larger proportion of the soil on these plots remains unmoved and becomes age hardened, leading in time to greater strength characteristics than on the tractor plots. This does not occur on the ploughed plots because all the soil to cultivation depth is loosened annually.

Table 10
Cone penetration resistance on the tine cultivated plots, April 1993

	Depth mm	*Tractor*	*Gantry*	*SED**
Soil water content, % dry basis	0–150	53·4	55·5	
		Cone resistance, MPa		
	0	0·123	0·182	0·030
	50	0·478	0·494	0·058
	100	0·692	0·662	0·066

* SED standard error of differences of means.

The future of controlled traffic systems based on gantries relies, as with most other systems, on economics. The contribution of this paper is considered to be a demonstration that gantries are a practical approach to controlled traffic operations and that they allow, on a practical scale, the possibility of separating the cropped and wheeled areas of a field. Their span will be determined by both practical and economic considerations, the latter relying on both engineering inputs as well as crop responses. In our study with cereals, yield responses were very variable, but a review of cereal crop research worldwide would indicate that an average yield increase of about 7% may be expected (Chamen and Audsley,[44] pp. 372–374). In this desk top study,[44] these and other data relating to zero traffic systems indicated that with the high capital cost of gantry systems, a cereal yield increase of about 7% was needed to maintain farm profitability compared with conventional practice.

7. Conclusions

The engineering of gantries, as distinct from tractors, is associated with the fundamental difference in their widths and the effect this has on their structure and operation. Several years of use of these vehicles, both for research and as part of an arable crop farm mechanization system, have shown that there is no major obstacle to their use as a replacement for or as a complement to existing tractor systems. The power-to-weight ratio of hydrostatically driven two-wheel drive gantries used in this context should be a minimum of 15 kW/t of vehicle mass. There is no single gantry span which can be identified as an optimum for all situations.

The stability of gantries on sloping ground is not a problem unless high ratios of drive to castor wheel load (greater than 75:25) are used. Steering stability of a gantry is not affected by implement loads offset from the centre line of the machine, providing sufficient drive torque and traction are available at the wheel or wheels required to transmit the load.

Bout matching and applicator boom stability are potentially superior to those provided by conventional tractor systems. Comparative measurements of the performance of the two systems in these respects should be made to quantify differences.

Operationally, gantries need good driver vision of the wheelways, means of driving lengthways, limited protrusion of their structures outside the wheelspan and a differential wheel speed facility. The performance of long-term soil-based wheelways can only be assessed when these are widely used on commercial farms with a fully developed gantry system.

Removing all traffic from cultivated soil reduces the energy required for seedbed preparation and reduces plough resistance by around 45%. In seasons which do not show this saving, it is concluded that this reflects a lack of damage in the presence of traffic due to dry conditions, rather than the absence of improvements where traffic has been avoided.

Where a gantry is used for cereal crop production significant increases in yield can be obtained.

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