A study on bullock carts. Part 2. Experimental study of forces in a bullock cart

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MS received 20 October 1979

Abstract. A strain gauge load cell with separate bridges for measurement of the pull and the bending moment in the plane containing the net neck load and pull was developed and fixed in the longitudinal member of an experimental cart. A cart fitted first with pneumatic wheels and then with steel-rimmed wooden wheels was tested on three terrains—tar road, mud road and grassy terrain. Pull vs time and moment vs time records were obtained in each test and analysed.

It is found that the bullocks pull the cart rather discontinuously at the low velocities at which these carts normally operate. On the tar road and the grassy terrain, the mean static coefficient of friction is significantly higher for the cart with steel-rimmed wooden wheels. The dynamic frictional resistance of the terrain for the cart with steel-rimmed wooden wheels is lower than for the cart with pneumatic wheels so long as the wheels do not dig or sink into the terrain. The fluctuation in the neck load is lower in the cart fitted with pneumatic wheels. Also, the ground-induced low-amplitude high-frequency vibratory load content in the neck load is lower in the cart with pneumatic wheels.

Keywords. Bullock cart; experimental cart; measurement; strain gauge load cell; calibration; frictional resistance.

1. Introduction

The net load capacity of conventional and two-wheel pneumatic (Dunlop ADV tyres) tyre carts are claimed to be about 1 tonne and 2.5 tonnes respectively (Anon 1977). From steady static tests some comparative data have been obtained on the effective rolling friction μ (combined ground friction and bearing friction) offered in cases of steel-rimmed wheels and pneumatic tyres on a few typical terrains. The data given in table 1 (Marks 1951) show that μ for pneumatic tyres on concrete road is slightly more than for steel-rimmed wheels. On other terrains, μ for pneumatic tyres is only 15 to 25% lower. This implies that the draw-bar pull in carts fitted with pneumatic tyres is about 1.6 to 1.75 that of conventional carts if it has to carry 2.5 times the net load carried by conventional carts. No data are available on the effect of carrying such heavier loads on the necks of the bullocks and their life.

In a series of investigations conducted more than three decades ago (Vagh 1944-51) several designs for the steel-rimmed wooden bullock-cart wheel were tested in a cart pulled manually by several persons. A special spring-dynamometer involving the use of a third wheel in front was used to record on a drum recorder the variation of draw-bar pull during the test. The spring-dynamometer-cum-recorder is perhaps

A list of symbols appears at the end of the paper.

Table 1. Data on μ for pneumatic and steel-rimmed wheels (Marks 1951)

Type of Wheel	Load kgf	Surface			
		Concrete	Blue grass sod	Tilled loam	Loose sand
Wheel with steel tyres (diameter 60 to 120 cm; width: 6.3 to 20 cm)	227– 682	0.010– 0.034	0.065– 0.094	0.236– 0.468	0.264– 0.504
Pneumatic tyres (4–18 to 7.5–36; 9–16; 4 to 6 ply) (tyre pressure: 1.1–2.5 kg/cm ²)	227– 682	0.017– 0.042	0.050– 0.070	0.185– 0.401	0.177– 0.460

unsuitable for use with bullocks providing the tractive effort. These tests were conducted on concrete, water-bound (WB) Macadam and earth roads. From draw-bar pull and minimum damage to road considerations, it was claimed that the steel-rimmed wooden wheels (conventional design) are satisfactory provided the tyre width is increased from 5 cm to 7.5 cm.

However, no detailed analysis has been reported in the literature on μ and the dynamic effects on the pull and neck loads under actual operating conditions. Hence, in the present study, a two-wheel cart was fitted with a strain gauge load cell specially designed for this purpose. The instrumented cart provided independent records of pull and neck load under actual operating conditions. Details about this instrumented cart and analysis of the results of tests wherein this cart fitted first with pneumatic tyres and then with conventional steel-rimmed wheels was operated on various types of terrains, are presented here.

For an experimental study of the performance of a two-wheel bullock cart fitted with either steel-rimmed wooden wheels or pneumatic wheels and operating on various types of terrains, the forces exerted by the bullocks on the cart have to be measured under actual operating conditions. A load cell is required to measure these forces. An important requirement this load cell has to satisfy is that its introduction into the system should not significantly alter the characteristics of the bullock cart. The load cell and the associated instruments should faithfully record the dynamic variations of these forces i.e., the pull and the neck load, while the cart is in motion. A study of various measuring devices show that a strain gauge load cell fitted in the longitudinal member (figure 1) of the cart is well suited for this purpose.

2. Strain gauge load cell

A load cell located in the longitudinal member of the cart is subjected to the following forces and moments (figure 1)

$$P = P_1 + P_2, \quad (1a)$$

$$W_R = W_{R1} + W_{R2}, \quad (1b)$$

Figure 1. Forces on the yoke of the bullock cart

$$M_{ll} = W_R y - P x, \quad (1c)$$

$$M_{nn} = P_1 v_1 - P_2 v_2, \quad (1d)$$

$$T = W_{R1} v_1 - W_{R2} v_2, \quad (1e)$$

where P_1 and P_2 are the pulls exerted by the two bullocks and W_{R1} and W_{R2} are the corresponding neck loads on the bullocks.

The load cell should satisfy the following important requirements:

- (i) it should be capable of measuring at any instant both P and W_R ;
- (ii) the output of the load cell corresponding to P should be insensitive to the magnitude of the shear force W_R , the bending moments M_{ll} and M_{nn} and torque T ;
- (iii) the output of the load cell corresponding to the neck load W_R could either indicate directly the neck load or give the neck load indirectly through the bending moment M_{ll} . In the present design it was found convenient to measure M_{ll} . The load cell output indicating this bending moment should be unaffected by the stresses in the load cell due to the axial load P , shear force W_R , bending moment, M_{nn} and torque T .
- (iv) The stiffness of the load cell in both longitudinal and transverse directions should preferably be greater than the stiffness of the longitudinal wooden member.

A strain-gauge load cell which satisfies all these requirements is shown in figures 2 and 3. In this load cell, four stainless steel octagonal rings each having 40 mm inside diameter and 3 mm minimum wall thickness, are sandwiched between two 15 mm thick mild steel plates. Bolts (8 mm diameter) and nuts are used to fix these rings to the

Figure 2. Forces and moments on the load cell

Figure 3. Load cell assembly

Figure 4. Load cell output recording system

steel plates. Sixteen 120Ω strain gauges (*Satya* gauge type SA-12-STCL, grid length 5 mm) are fixed on these rings as shown in figure 2. These strain gauges are connected as shown in figure 4 to form two half-bridges for measuring directly P and M_{II} . The half bridges are connected to a Kelvin and Hughes four-pen recorder through Phillips strain meters and preamplifiers (figure 4). The excitation voltage (220 V 50 cycles AC) for the strain-measuring system was obtained through a petrol engine-generator set mounted on the platform of the cart (figure 5, plate 1). An automatic voltage regulator was used to obtain steady voltage supply. All measuring instruments and associated equipment were mounted on the platform of the cart (figure 5, plate 1).

Some design details on the load cell are given in figure 3. As may be seen in this figure, stops are provided to prevent the overloading of the load cell. The longitudinal wooden member in the cart is cut at a station about 30 cm from the yoke end and the load cell is fixed between the cut pieces through angles, bolts and nuts (figure 3).

3. Calibration of the load cell

The four octagonal-faced rings with strain gauges fixed on them were individually tested in compression in an universal testing machine for checking the satisfactory performance of the strain gauges. The load cell was then assembled and tested in tension in the universal testing machine. After ensuring satisfactory performance of the load cell the stops were adjusted to limit the maximum axial load to 500 kgf and bending moment to 30 kgfm. The load cell was then fixed as described earlier to the longitudinal member of the cart and instrumented. It was then calibrated for axial load and bending moment.

The set-up used for axial load calibration through dead weights is shown in figure 6 (an additional joint provided in the longitudinal wooden member between the load cell and the wooden platform facilitated this test). The calibration constant for axial load was found to be $1.03 \mu\epsilon/\text{kgf}$. The cross sensitivity i.e., the ratio of the outputs of the bending moment bridge and the axial load bridge, was less than 2%.

Two arrangements shown in figure 7 were used for bending moment calibration through dead weights. In one set-up (figure 7a) vertical loads were applied on the yoke

Figure 6. Set-up for axial load calibration using dead weights.

Figure 7. Arrangements for bending moment calibration with simulated load W_R .

at the locations where the yoke rests on the two bullocks. In the other set-up (figure 7b), a vertical load was applied directly to the longitudinal member at the section where the yoke transmits in the actual cart, load to the longitudinal member. Both tests gave the same calibration constant of $3.3 \mu\epsilon$ per kgf vertical load in the yoke i.e., 9.3 kgcm bending moment per $\mu\epsilon$.

During the actual test, a shunt resistance was used to calibrate the axial load measuring system in terms of pen deflection per unit micro strain on the strain meter. This used along with the calibration constant of the load cell in terms of microstrain per unit axial load i.e., $1.03 \mu\epsilon/\text{kgf}$ gave the calibration constant for the axial load measuring system in terms of load per millimeter pen deflection; this calibration constant was about 29.5 kgf/mm deflection of the pen recorder.

In the case of bending moment measuring system, the calibration constant in terms of pen deflection per unit microstrain was found at the commencement of each test by applying a static lateral load on the yoke of the cart. This data used along with

calibration constant from the earlier calibration test i.e., $3.3 \mu\epsilon/\text{kgf}$ vertical load gave the calibration constant of the bending moment measuring system in terms of kgf per mm pen deflection. About 10 kgf vertical load on the yoke produces 1 mm deflection of the pen of the recorder.

From the measured values of the bending moment M_H and the pull P the corresponding neck load can be determined through equation (1c). Thus

$$W_R = (M_H/y) + (Px/y). \quad (2)$$

4. Test conditions

The experimental cart fitted alternately with conventional steel-rimmed wheels and pneumatic wheels were tested on three types of terrains located around the Internal Combustion Engineering building of the Indian Institute of Science, Bangalore. The specifications of the experimental cart and details about the pneumatic and wooden wheels are given in table 2. The three types of terrains are:

- (i) tar road: two strips hereafter termed as tar road 1 and tar road 2;
- (ii) dry mud road: a stretch of road with a thin layer of mud over compacted stone jelly and sand;
- (iii) unprepared grassy (green grass) terrain.

Table 2. Specification of the experimental cart

1. General:

Platform size: 218 cm $\times$ 82.5 cm (86 in. $\times$ 32.5 in.)
 Platform height from the ground: 106 cm (41.8 in.)
 Distance between the wheel centre and the neck of the bullocks, $c=283$ cm (111.5 in.)
 Height of the neck of the bullocks from the ground $h=100$ cm (40 in.)
 Centre distance between the bullocks (necks): 107 cm (42 in.)

2. Steel-rimmed wooden wheels

Diameter D_w : 150 cm (60 in.)
 Width : 5 cm (2 in.)
 Thickness of steel belt: 1.5 cm (0.6 in.)
 No. of spokes: 12
 Axle diameter: 3.2 cm (1.25 in.)
 Weight of each wheel: 86.2 kgf (190 lb.)
 Centre distance between the wooden wheels on the cart: 126 cm (49.5 in.)

3. Pneumatic wheels

Specification: S75-6-00-16, 6 ply rating
 Type: New Deluxe Champion of M/s Firestone
 Outside diameter of inflated wheels: 70 cm (27.5 in.)
 Tread width: 11 cm (4.3 in.); Tread partially worn
 Weight of pneumatic wheels with axle and tie rod assembly: 71.2 kgf (157 lb.)
 Centre distance between the wheels: 128 cm (50.5 in.)
 Tyre pressure: 1.4 and 2.1 kgf/cm² (20 and 30 psig)

5. Test procedure

Besides the strain measuring equipment and the engine-generator set, cast iron weights were placed in the cart in suitable positions to provide the required load on the cart. The static neck load on the two bullocks with the cart driver in position was in the range of 40 to 56 kgf.

At the commencement of each test, the platform of the experimental cart (without the bullocks) was made horizontal by supporting the longitudinal member at a point between the load cell and the platform so that there was virtually no load on the load cell. The engine-generator set was then started and the strain measuring bridges were activated and allowed to warm up. After balancing the bridges for capacitance and resistance unbalance, both the bridges were calibrated as described above. The support to the longitudinal member was removed before the bullocks were tied to the cart. The cart was then moved to the starting point marked on each terrain. The recorder was switched on just before the cart driver drove the cart over the test length of the terrain. The pens recorded the pull and bending moment M_H throughout the test. The recorder was switched off at the end of the test. The average velocity of the cart was determined with a stop-watch by clocking the time taken by the cart to cover the test length. The cart was then turned round for operation over the same stretch in the reverse direction. During this test also, pull and bending moment records were obtained and the average speed of the cart was also determined.

6. Analysis of test data

The experimental cart fitted with pneumatic wheels was run with tyre pressure of 1.4 (20 psi) and 2.1 kgf/cm² (30 psi) on each chosen terrain both in the forward and reverse directions. The pneumatic wheels were then removed to fit the cart with conventional steel-rimmed wooden wheels. The experimental cart with conventional steel-rimmed wheels was then tested over the same terrains the pneumatic wheel cart was tested. Pull and bending moment records were obtained in all cases. A typical set of pull vs time and moment vs time records is given in figure 8.

A study of the pull vs time records shows that the bullocks pull the cart rather discontinuously. The waviness in the pull vs time record is ascribed to the discontinuous motion of the bullocks as they walk along pulling the cart. As may be

Figure 8. Typical record of pull and neck load.

seen from equation (1c), the low frequency waviness in the bending moment vs time records is due to modulation of the bending moment W_{Ry} due to the neck load by the bending moment Px arising from the discontinuous pull.

To facilitate measurements, all the records were magnified with the aid of an epidiascope. The heights of peaks and valleys in each record were estimated to an accuracy of ± 0.1 mm*.

The relatively high frequency low amplitude peaks in these records were attributed to dynamic effects arising partly from the wheel and terrain interaction and partly from the variation in the motion of the bullocks. To filter off most of these disturbances only peaks/valleys of amplitude greater than about 0.5 mm were measured and used in the analysis.

6.1 Analysis of pull vs time records

On each record, the height of the peak(s) h_s at the start of the motion was measured from the zero load (reference) line to estimate the force required to set the cart in motion. This data is used to estimate the static effective coefficient of friction μ_s .

The average pull is determined from

$$\bar{P}_{d(\max)} = C_p \sum_{i=1}^n h_{pi}/n, \quad (3)$$

where $h_{p1}, h_{p2} \dots h_{pi} \dots h_{pn}$ are the amplitudes of the peaks in mm in the pull vs time record, n is the number of peaks (peak(s) h_s are omitted from this analysis), and C_p is the calibration constant in kg/mm. This data is used to estimate the mean dynamic effective coefficient of friction $\bar{\mu}_d$.

From the heights of the valleys h_v in the pull vs time record, the average minimum pull is estimated

$$\bar{P}_{d(\min)} = C_p \sum_{i=1}^n h_{vi}/n = \sum_{i=1}^n P_{di(\min)}/n. \quad (4)$$

The mean amplitude of fluctuation in the pull is calculated from:

$$\bar{P}_{da} = \bar{P}_{d(\max)} - \bar{P}_{d(\min)}. \quad (5)$$

6.2 Analysis of bending moment vs time records

As the bending moment due to the pull acts in a direction opposite to the bending moment due to the upward neck load, a peak in the pull vs time record should correspond to a valley in the bending moment vs time record and vice versa.

From equation (2) the mean neck load $\bar{W}_{Rp}$ can be determined

$$\bar{W}_{Rp} = \sum_{i=1}^n W_{Rpi}/n = \left(C_n \sum_{i=1}^n h'_{pi}/n \right) + P_{d(\min)} \frac{x}{y}, \quad (6)$$

*For checking the accuracy of measurement with the epidiascope, some records were analysed more accurately with a travelling microscope. This check showed that the error in analysis based on epidiascope measurements was less than 5%.

where h'_{pi} are the heights of peaks in the bending moment vs time record C_n is the calibration constant for conversion of moment data, h'_{pi} in mm of pen deflection to equivalent vertical load or neck load on the bullocks.

The mean neck load $\bar{W}_{Rv}$ is given by

$$\bar{W}_{Rv} = \sum_{i=1}^n W_{Rvi}/n = (C_n \sum_{i=1}^n h'_{vi}/n) + \bar{P}_{d(\max)} \frac{x}{y}, \quad (7)$$

where h'_{vi} are the heights of valleys in the bending moment vs time record and n is the number of valleys used in the computation.

$$\text{Also, } \bar{W}_{Ra} = \bar{W}_{Rp} - \bar{W}_{Rv}, \quad (8)$$

where $\bar{W}_{Ra}$ is the mean amplitude of the fluctuation in the neck load.

6.3 Estimation of coefficients of friction

For eliminating the error due to gradient variations in the terrain in the estimation of $\bar{\mu}_d$, the experimental cart was run in both forward and return directions on the same terrain. If $P_{di(\max)}$ and $P'_{di(\max)}$ are the pull required to negotiate in the forward and return directions respectively on the i th elemental length of the terrain of gradient θ , then from equation (11) of Part 1 (Raghavan & Nagendra 1979)

$$P_{di(\max)}/W_L = \mu_d (\cos \theta - (W_{Rvi})/W_L) + \sin \theta, \quad (9a)$$

$$P'_{di(\max)}/W_L = \mu_d (\cos \theta - (W'_{Rvi})/W_L) - \sin \theta, \quad (9b)$$

where W_{Rvi} and W'_{Rvi} are the corresponding neck loads in the forward and return directions respectively. (As the cart velocities are quite low, the acceleration a_c is neglected). Hence

$$[P_{di(\max)} + P'_{di(\max)}]/2 W_L = \mu_d \{ \cos \theta - [(W_{Rvi} + W'_{Rvi})/2 W_L] \}. \quad (10a)$$

As for gradients less than 1 in 5, the error due to replacing $\cos \theta$ by 1 is less than 2% equation (10) is simplified:

$$[P_{di(\max)} + P'_{di(\max)}]/2 W_L = \mu_d \{ 1 - [(W_{Rvi} + W'_{Rvi})/2 W_L] \}. \quad (10b)$$

If there are n such elemental lengths in the test length, the mean dynamic effective coefficient of friction is given by

$$\bar{\mu}_d = \left\{ \sum_{i=1}^n 0.5 [P_{di(\max)} + P'_{di(\max)}] \right\} / n W_L \left[1 - \sum_{i=1}^n (W_{Rvi} + W'_{Rvi})/2n W_L \right], \quad (11a)$$

$$= 0.5 [\bar{P}_{df(\max)} + \bar{P}_{dr(\max)}] / W_L [1 - (\bar{W}_{Rvf} + \bar{W}_{Rvr})/2 W_L], \quad (11b)$$

where $\bar{P}_{df(\max)}$ and $\bar{P}_{dr(\max)}$ are the mean values of pull, $\bar{P}_{d(\max)}$ (see equation (3)) in the forward and return run respectively, $\bar{W}_{Rvf}$, and $\bar{W}_{Rvr}$ are the corresponding mean

values for the neck load $\bar{W}_{Rv}$ (see equation (7)) for forward and reverse runs respectively. Similarly the mean static effective coefficient of friction is given by

$$\bar{\mu}_s = 0.5 (\bar{P}_{sf} + \bar{P}_{sr}) / W_L \{1 - [(\bar{W}_{Rsf} + \bar{W}_{Rsr}) / 2 W_L]\}, \quad (12)$$

where $\bar{P}_{sf}$ and $\bar{P}_{sr}$ are the mean peak load at the start of the motion of the cart in the forward and reverse runs respectively. $\bar{W}_{Rsf}$ and $\bar{W}_{Rsr}$ are the corresponding neck loads in the forward and reverse runs respectively.

7. Discussion of test results

Test records obtained under various operating conditions for carts fitted with pneumatic and steel-rimmed wooden wheels were analysed as described above. The results of these analyses are presented in tables 3 and 4.

The average speed of the cart was in the range of 3 to 4 km/hr. The total weight W_L of the cart fitted with pneumatic and steel-rimmed wooden wheels were 830 kgf (1830 lb) and 932.5 kgf (2056 lb) respectively. The height h of the neck of the bullocks was 100 cm (40 in.).

7.1 Pull vs time records

In the case of the cart fitted with pneumatic wheels, the mean static effective coefficient of friction $\bar{\mu}_s$ was about 0.25 on a tar road. On the mud road and the grassy terrain, it was higher and in the range of 0.265 to 0.315. On the tar road, the variation of tyre pressure from 1.4 (20 psig) to 2.1 (30 psig) kgf/cm² had no significant effect on $\bar{\mu}_s$. However, on the mud road and on the grassy terrain, this increase in tyre pressure caused a significant increase—from 0.265 to 0.315—in $\bar{\mu}_s$. Also at both the tyre pressures, $\bar{\mu}_s$ was essentially the same for both the mud road and the grassy terrain.

In the case of cart fitted with steel-rimmed wooden wheels, $\bar{\mu}_s$ on the tar road was somewhat lower than on the mud road. It was highest on the grassy terrain.

A comparative study (table 5) indicates that $\bar{\mu}_s$ for the cart with steel-rimmed wooden wheels is significantly higher than $\bar{\mu}_s$ for the cart with pneumatic wheels. It is 16% and 24% higher on the tar road and the grassy terrain respectively. However, on the mud road, $\bar{\mu}_s$ for the former cart is only slightly higher.

The mean dynamic effective coefficient of friction $\bar{\mu}_d$ for the cart fitted with pneumatic wheels was about the same (~ 0.08) on the tar road and the mud road. However, on the grassy terrain, it was higher and in the range 0.16 and 0.20. On the tar road and the mud road, tyre pressure variation from 2.1 (30 psig) to 1.4 (20 psig) kgf/cm² had no significant effect on $\bar{\mu}_d$. On the grassy terrain the same decrease in tyre pressure resulted in a significant (25%) decrease in $\bar{\mu}_d$.

In the case of the cart fitted with steel-rimmed wooden wheels $\bar{\mu}_d$ on the mud road and the grassy terrain were about 45% and 125% respectively higher than that on the tar road. A comparative study of $\bar{\mu}_d$ for the carts with steel-rimmed wooden wheels and pneumatic wheels indicates that the $\bar{\mu}_d$ for the former cart is 27% and 31% lower on the tar road and the grassy terrain respectively. On the mud road, however, $\bar{\mu}_d$ for the cart with steel-rimmed wooden wheels is only slightly higher.

Table 3. Analysis of data on pull P

Type of wheels	Terrain	Velo-city (km/hr)	At the start of motion				Dynamic forces					Mean coefficient of friction	
			$\bar{P}_s$ kgf (lb)	$\bar{P}_s/W_L$	P_{Rs} kgf (lb)	P_{Rs}/W_L	$\bar{P}_d$ (max)	$\frac{\bar{P}_d(\max)}{W_L}$	$\bar{P}_d$ (min)	$\frac{\bar{P}_d(\min)}{W_L}$	$\frac{\bar{P}_{da}}{\bar{P}_d(\max)}$	$\bar{\mu}_s$	$\bar{\mu}_d$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Pneumatic wheels; Tyre pressure: 2.1 kgf/cm ² (30 psig)	TR1	F 3.2	228 (503)	0.275	238 (523)	0.286	80.5 (177)	0.097	12.7 (28)	0.015	0.84	0.249	0.083
		R 3.2	151.5 (334)	0.182	167 (367)	0.20	50 (110)	0.060	10 (22)	0.012	0.80		
	MR	F 3.5	224 (494)	0.27	238 (524)	0.286	42 (92.5)	0.050	1.8 (4)	0.002	0.96	0.313	0.07
		R 3.5	243 (536)	0.293	260 (573)	0.313	67.5 (149)	0.081	26.3 (58)	0.032	0.61		
$W_L=830$ kgf (1830 lb)	GT	F 3	243.5 (537)	0.293	259 (571)	0.312	143.5 (316)	0.173	41.5 (91.5)	0.05	0.71	0.314	0.198
		R 3	224 (494)	0.27	239 (526)	0.288	159 (351)	0.192	68.5 (151)	0.082	0.57		
Pneumatic wheels Tyre pressure 1.4 kgf/cm ² (20 psig)	TR1	F 3.1	156 (344)	0.188	167 (367)	0.20	71 (157)	0.086	-9.5 (-21)	-0.011	1.13	0.223	0.091
		R 3.2	184 (406)	0.222	201.5 (443.5)	0.242	70 (154)	0.084	22 (48)	0.026	0.69		
		F 3.5	205.5 (453)	0.247	218 (479)	0.262	70.5 (155.5)	0.085	18.5 (40.5)	0.022	0.74	0.273	0.08
	TR2	R 3.3	210 (463)	0.253	222 (489)	0.267	54 (119)	0.065	10.7 (23.5)	0.013	0.80		
$W_L=830$ kgf (1830 lb)	MR	F 3.5	177.5 (391)	0.214	191.5 (421)	0.23	75.5 (166)	0.091	27 (60)	0.033	0.64	0.265	0.082
		R 3.8	226.5 (500)	0.273	236.5 (520.5)	0.284	52 (115)	0.063	10.5 (23.5)	0.013	0.8		
	GT	F 3	203 (448)	0.245	220.5 (485)	0.265	103 (227)	0.124	24.5 (54)	0.029	0.76	0.267	0.162
		R 3	199.5 (440)	0.24	212 (466.5)	0.255	144 (318)	0.174	64.5 (142)	0.077	0.55		

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Steel-rimmed wooden wheels $W_L=932.5$ kgf (2056 lb).	TR1	F 3.3	261 (576)	0.28	266.5 (586)	0.285	67.5 (149)	0.072	21 (46)	0.022	0.69	0.266	0.062
		R 3.7	206.5 (455)	0.221	215.5 (474)	0.231	44.5 (98)	0.048	6.3 (14)	0.007	0.86		
	TR2	F 3.85	252.5 (557)	0.271	262 (576)	0.28	48.5 (107)	0.052	9 (20)	0.010	0.81	0.314	0.054
		R 3.85	288.5 (636)	0.309	298 (656)	0.319	49.5 (109)	0.053	16 (35)	0.017	0.68		
	MR	F 3.85	183 (404)	0.196	193.5 (426)	0.207	93 (205)	0.10	56.5 (125)	0.061	0.39	0.301	0.084
		R 3.9	339 (747)	0.363	346.5 (762)	0.371	58 (128)	0.062	32.5 (72)	0.035	0.44		
	GT	F 3.35	339 (747)	0.363	345 (759)	0.369	114.5 (252)	0.122	73.5 (162)	0.079	0.36	0.359	0.132
		R 3.7	287 (633)	0.308	294.5 (648)	0.315	124.5 (274)	0.133	41 (90)	0.044	0.67		

Abbreviations: TR, tar road; MR, mud road; GT, grassy terrain; F, forward; R, return.

Table 4. Analysis of data on neck load W_R .

Type of wheels	Terrain	Velocity km/hr	Stationary cart		At start of motion				Dynamic			
			W'_R kgf (lb)	W'_R/W_L	$\bar{W}_{Rz}$ kgf (lb)	$\bar{W}_{Rz}/W_L$	$\frac{\bar{W}_{Rz}-W'_R}{W'_R}$	$\bar{W}_{Rp}$ kgf (lb)	W_{Rp}/W_L	$\bar{W}_{Rv}$ kgf (lb)	$\bar{W}_{Rv}/W_L$	$\bar{W}_{Rd}/W_{Rp}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Pneumatic wheels	F	3.2	40.8 (90)	0.049	65.8 (145)	0.079	0.61	49.4 (109)	0.059	34.5 (76)	0.041	0.30
Tyre pressure: 2.1 kgf/cm ² (30 psig) $W_L=830$ kgf (1830 lb)	R	3.2	40.8 (90)	0.049	69.4 (153)	0.084	0.7	57 (126)	0.069	53 (117)	0.064	0.07
	F	3.5	40.8 (90)	0.049	79.4 (175)	0.096	0.94	47.3 (104)	0.057	39.5 (87)	0.047	0.165
	R	3.5	45.3 (100)	0.055	92 (203)	0.111	1.03	59.5 (131)	0.072	56 (124)	0.068	0.055
	F	3	50 (110)	0.060	88.4 (195)	0.106	0.77	67.4 (148.7)	0.081	67.7 (149.2)	0.081	0
	R	3	50 (110)	0.060	82.5 (182)	0.099	0.65	83.2 (183.4)	0.100	68.1 (150.2)	0.082	0.18
Pneumatic wheels	F	3.1	45.3 (100)	0.055	57.6 (127)	0.069	0.27	48.7 (107.4)	0.059	48.7 (107.3)	0.058	0
Tyre pressure 1.4 kgf/cm ² (20 psi) $W_L=830$ kgf (1830 lb)	R	3.2	40.8 (90)	0.049	81 (178.5)	0.097	0.98	53.1 (117)	0.064	56.7 (125)	0.068	0.07
	F	3.5	42.2 (93)	0.051	70.7 (156)	0.085	0.68	51.2 (112.7)	0.062	49.8 (109.8)	0.06	0.025
	R	3.3	51.2 (113)	0.062	71.7 (157)	0.086	0.39	51 (112.4)	0.062	52.3 (115.4)	0.063	0.025
	F	3.5	45.3 (100)	0.055	71 (156.4)	0.085	0.56	54.1 (119.4)	0.065	56.3 (124)	0.068	0.04
	R	3.8	51.2 (113)	0.062	65.5 (144.5)	0.079	0.28	54.6 (120.4)	0.066	49.5 (109)	0.059	0.095
	F	3	55.8 (123)	0.067	84.2 (185.6)	0.101	0.51	65.7 (145)	0.079	67.2 (148.3)	0.081	0.025
	R	3	51.2 (113)	0.062	70.3 (155)	0.085	0.37	69.4 (153)	0.084	63.8 (140.8)	0.077	0.08

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Steel-rimmed wooden wheels $W_L=932.5 \text{ kgf}$ (2056 lb)	F	3.3	44 (97)	0.047	48.5 (107)	0.052	0.105	52 (115)	0.056	26.2 (57.8)	0.028	0.50
	TR1											
	R	3.7	42.2 (93)	0.045	60.8 (134)	0.065	0.44	49.6 (109.4)	0.053	31.2 (68.8)	0.033	0.37
	F	3.85	44 (97)	0.047	66.2 (146)	0.071	0.505	50.7 (111.8)	0.054	22 (48.6)	0.024	0.565
	RT2											
	R	3.85	40.8 (90)	0.044	73.9 (163)	0.079	0.81	49 (108)	0.052	28.7 (63.2)	0.031	0.415
	F	3.85	40.8 (90)	0.044	61.2 (135)	0.066	0.50	66.3 (146.2)	0.071	29.4 (64.8)	0.031	0.56
	MR											
	R	3.9	46.7 (103)	0.05	68.9 (152)	0.074	0.475	54.7 (120.6)	0.059	26.4 (58.2)	0.028	0.52
	F	3.35	48.5 (107)	0.052	60.3 (133)	0.065	0.245	71.2 (157)	0.076	36.8 (81)	0.039	0.485
	GT											
	R	3.7	44 (97)	0.047	62.1 (137)	0.067	0.41	51.4 (113.3)	0.055	20 (44)	0.021	0.61

Abbreviations: TR, tar road; MR, mud road; GT, grassy terrain; F, forward; R, return.

Table 5. $\bar{\mu}_s$ and $\bar{\mu}_d$ for bullock carts with pneumatic wheels and with steel-rimmed wooden wheels.

Terrain	Cart with pneumatic wheels				Cart with steel-rimmed wooden wheels			
	$\bar{\mu}_s$		$\bar{\mu}_d$		$\bar{\mu}_s$		$\bar{\mu}_d$	
	Range	Mean value	Range	Mean value	Range	Mean value	Range	Mean value
Tar road	0.22–0.27	0.25	0.08–0.09	0.085	0.26–0.31	0.29	0.05–0.06	0.058
Mud road	0.265–0.315	0.29	0.07–0.08	0.075	—	0.30	—	0.084
Grassy terrain	0.265–0.315	0.29	0.16–0.20	0.18	—	0.36	—	0.132

For both types of carts, the mean amplitude of fluctuation of the pull $\bar{P}_{da}$ on a tar road is in the range of 68 to 85% of the $\bar{P}_{d(\max)}$. However, on the mud road and the grassy terrain, $\bar{P}_{da}$ for the cart with steel-rimmed wooden wheels is significantly lower.

7.2 Neck load

In all these tests, the neck load W'_R on the stationary bullocks (just before they start moving the cart) was set at a value in the range of 40 to 56 kg. At the start of the motion of the cart due to the force exerted by the bullocks the neck load increased considerably. This increase in the neck load i.e., $(\bar{W}_{Rs} - W'_R)/W'_R$ at the start of the motion in the case of the cart with pneumatic smaller wheels was higher; the mean value was 0.62. The corresponding value for the cart with larger diameter steel-rimmed wooden wheels was 0.44.

The increase in the mean neck load $(\bar{W}_{Rp} - W'_R)$ in the moving cart was maximum on the grassy terrain. On the tar road and the mud road, the increase in the mean neck load $(\bar{W}_{Rp} - W'_R)$ was about the same for both types of carts. The mean amplitude of fluctuation in the neck load $(\bar{W}_{Ra}/\bar{W}_{Rp})$ was the lowest in the cart with pneumatic wheels inflated to a pressure of 1.4 kgf/cm² (20 psig); it was less than 0.1. An increase in tyre stiffness due to increase in pressure from 1.4 to 2.1 kgf/cm² resulted in a higher $\bar{W}_{Ra}/\bar{W}_{Rp}$. It was the highest for the cart fitted with stiff steel-rimmed wooden wheels and was in the range 0.37 to 0.61.

It was also observed that the bullocks were subjected to a ground-induced vibratory neck load of low amplitude but of a relatively higher frequency. The ground-induced vibrating load content was significantly higher in the case of the cart fitted with steel-rimmed wooden wheels.

8. Conclusions

A strain-gauge load cell with separate bridges for measurement of the pull and the bending moment in the plane containing the net neck load and pull, was developed and fixed in the longitudinal member of an experimental cart at a section about 30 cm

from the yoke end. The outputs from these bridges were connected to a Kelvin and Hughes pen recorder through separate strain meters and amplifiers. Both the pull and moment measuring systems were finally calibrated *in situ*. A cart fitted first with pneumatic wheels and then with steel-rimmed wooden wheels was tested on three types of terrains—tar road, mud road, and grassy terrain. Pull vs time and moment vs time records were obtained in each test and analysed using the procedure developed.

The analysis of all the test records reveal:

(i) The bullocks pull the cart rather discontinuously at the low velocities (3 to 4 km/hr) at which these carts normally operate. For both types of carts—carts fitted with either pneumatic wheels or steel-rimmed wooden wheels—on the tar road, the mean amplitudes of fluctuation of the pull $\bar{P}_{da}$ is in the range of 68 to 85% of the average pull $\bar{P}_{d(max)}$. However, on the mud road and the grassy terrain $\bar{P}_{da}$ for the cart with steel-rimmed wooden wheels is significantly lower.

(ii) On the tar road and the grassy terrain, the mean static coefficient of friction for the cart with steel-rimmed wooden wheels is significantly higher than for the cart with pneumatic wheels. On the mud road however $\bar{\mu}_s$ for the former cart is only slightly higher.

(iii) The mean dynamic coefficient of friction for the cart with steel-rimmed wooden wheels is 27 and 31% lower on the tar road and grassy terrain respectively. On the dry hard mud road, however, $\bar{\mu}_d$ of the cart with steel-rimmed wooden wheels is only slightly higher than for the cart with pneumatic wheels.

These results show that the dynamic frictional resistance of the terrain ($\bar{\mu}_d$) for the cart fitted with steel-rimmed wooden wheels is lower than for the cart with pneumatic wheels so long the wheels do not dig or sink into the terrain. On a dry hard mud road, $\bar{\mu}_d$ for both types of carts are comparable chiefly due to the increased deformation of the terrain in the case of cart with steel-rimmed wooden wheels. Increase in the width of the wheels would minimise the deformation of the terrain.

(iv) The increase in the neck load on the bullocks was maximum at the start of motion of the cart. Also this increase in the neck load was higher for the cart with pneumatic smaller wheels.

The average increase in the neck load while the cart is in motion was maximum on the grassy terrain. On the tar road and the mud road however this increase in the neck load was about the same for both types of carts.

(v) The mean amplitude of fluctuation in the neck load, $\bar{W}_{Ra}$ was the lowest in the case of cart fitted with pneumatic wheels having a tyre pressure of 1.4 kgf/cm². $\bar{W}_{Ra}$ was the highest for the cart fitted with the relatively stiff steel-rimmed wooden wheels.

The ground-induced low-amplitude high-frequency vibratory load content in the neck load was also large in the case of cart fitted with the steel-rimmed wooden wheels. Thus, due to inherent damping, the discomfort caused to the bullocks due to neck load fluctuations is significantly less in the case of cart fitted with pneumatic wheels.

(vi) The experimental results indicate that there is a need to develop an alternative wear-resistant material for the rim of the wooden wheels, which has built-in damping and a stiffness considerably lower than that of steel, e.g., a rubber composite.

The work reported here was carried out under a project sponsored by the Tata Energy Research Institute, Bombay. The authors gratefully acknowledge the encouragement and help received from Prof. A K N Reddy of Indian Institute of Science, Bangalore. The authors are grateful to Mr P V Reddy, for his enthusiastic and valuable assistance in the development of the load cell and in the experiments on the cart; to Mr P R Arora for his assistance in the calibration of the load cell; to Mr K R Hariharan, Mr H S Sathyanarayana and Mr. H R A Iyengar, Mr V S Anthony and Mr Muniswamy for their untiring help in conducting the experiments on the cart; to Mr P Srikanth and Mr T S Shanker, M.E.Course students of the Department of Mechanical Engineering, Indian Institute of Science for their assistance in the load cell design; to Mr C Shankaranarayana Rao for his assistance in preparing the figures; to Mr S Narayana Das for his assistance in photography. Help given by the M E Workshop staff in the fabrication of the load cell is gratefully acknowledged.

List of symbols

a_c	acceleration of cart in the direction of motion (cm/s ²)
C_n	calibration constant to convert moment data in mm of pen deflection to equivalent neck load (kgf/mm)
C_p	calibration constant to convert pull data in mm of pen deflection to corresponding pull (kgf/mm)
h	amplitude in pull vs time record (mm)
h'	amplitude in moment M_{II} vs time record (mm)
M_{II}	bending moment about axis II (figure 1)
M_{nn}	bending moment about axis nn (figure 1)
n	number of values or events
P	pull exerted by the bullocks on the cart (kgf)
$P_{di(max)}$	magnitude of i th peak in kgf in the pull vs time record (kgf)
$P_{di(min)}$	magnitude of i th valley in kgf in the pull vs time record (kgf)
$\bar{P}_{d(max)}$	average maximum pull (kgf)
$\bar{P}_{d(min)}$	average minimum pull (kgf)
$\bar{P}_{da}$	mean amplitude of fluctuation in pull
P_R	$(P^2 + W_R^2)^{1/2}$: resultant force exerted by the bullocks on the yoke
T	torque on the load cell (kgf/cm) (figure 1)
W_L	total load on the cart (kgf)
W_R	neck load on the bullocks (kgf)
$\bar{W}_{Rv}$	average neck load corresponding to peaks in the moment vs time record (kgf)
$\bar{W}_{Rv}$	average neck load corresponding to valleys in the moment vs time record (kgf)
$\bar{W}_{Ra}$	mean amplitude of fluctuation in the neck load
θ	slope of the terrain (degree)
$\bar{\mu}_d$	mean dynamic effective coefficient of friction
$\bar{\mu}_s$	mean static effective coefficient of friction
$\mu\epsilon$	microstrain

Subscripts

<i>a</i>	amplitude
<i>d</i>	dynamic
<i>f</i>	forward journey
<i>i</i>	ith value
<i>p</i>	peak
<i>r</i>	return or reverse journey
<i>s</i>	static
<i>v</i>	valley

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Figure 5. Experimental bullock cart. 1. Strain meter. 2. Kelvin and Hughes recorder. 3. Preamplifier. 4. Engine generator set. 5. Load cell. 6. Axle for steel-rimmed wooden wheels.