Dynamic behaviour of high-powered agricultural tractor for haulage operation

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ABSTRACT: Efficient utilization of tractor includes maximizing fuel economy as well as maximizing traction potential with optimum stability. The present study was taken up to develop an instrumented tractor for conducting haulage performance tests of a 39 kW PTO power of tractor to its dynamic behavior. Dynamic behaviour deals with safety, stability and mobility of tractor in different terrain conditions. The haulage performance parameters include draft, vertical force and stability. The tractor was instrumented with coupling mouth consisted two load cells of 5 ton capacity at single hitch point. The wheel reactions under dynamic condition were calculated to evaluate the stability index of tractor. Based on the desire stability index of 20 %, the maximum safe haulage capacity of test tractor was found to be 15000 kg on plane surface. However on 4 degree uphill and 4 degree downhill slopes the loading capacity was reduced to 13000 kg and 14000 kg.

Key words: Draft, haulage, instrumentation, stability index, trailer

Dynamic behaviour deals with stability, operational safety and mobility of tractor in different terrain conditions. Operational safety is the important consideration to protect the tractor operator from any hazards. It is possible if tractor is stable during static and dynamic conditions. It has been reported earlier that rearward overturning are more likely to fatal than the sideways overturning (National Safety Council, 1968). Rearward overturning takes place when dynamic front wheel reaction is reduced to zero due to excessive drawbar loading or rear wheel slippage. Historical data shows the fatality rate in agriculture remained about 18.3/ 100,000 workers through the 2007, while tractor-related accidents cause approximately 31% accidents in the farm machines categories (ICAR, 2007). Even with enormous efforts to improve tractor safety designs, the rate of tractor-related fatalities has shown a slight increase mainly due to the in adequate maneuvering of the tractor.

The ground reactions against the rear and front wheels are greatly affected by the variations in draft force, terrain conditions and operating parameter such as forward speed. Computations of these reactions help to determine the stability of tractor for haulage. Dynamics of tractor gives safe pulling ability in field and haulage operation with optimum stability. Sahu and Pandey (2005) did the haulage performance with single and double axle trailer. They measured draft, speed and fuel consumption and find out the transport productivity and fuel economy index. They developed a window based simulation program on haulage performance of a 2WD tractor-single axle trailer system for different terrains and operating conditions. Datta (2011) did the haulage performance of 2WD tractor with single axle trailer with 3000 kg and 4000 kg payload in different throttle condition. They found a suitable combination of gear and throttle for best fuel economy. Kumar and Pandey (2012) developed a microcontroller based system to measure and display the dynamic soil reactions against the front wheels to safeguard the rearwards overturning of agricultural tractors.

The high hp tractors are in great demand due to their use in haulage work as well as in land reclamation operations (Mehta *et al*., 2014; Tiwari *et al*., 2019a; Tiwari *et al*., 2019b; Kumar and Pandey 2016; Kumar *et al*., 2019; Sahu *et al*., 2013).. The use of such tractors for loader applications is increasing in many areas. There is a need to assess the suitability of such tractors for different field and haulage applications and determine optimum pay load capacity for safer operations. Keeping these points in view the present study has been taken to evaluate the dynamic behaviour of Eicher Harvester model of 39 kW PTO power for haulage operations with the optimum trailer load capacity and stability on varying terrain conditions.

THEORETICAL CONSIDERATIONS

The following theoretical and empirical equations were used to calculate various parameters for predicting dynamic wheel reactions and stability index. The tractor stability and steer ability are limited by the dynamic load transfer from the front axle to the rear axle.

Tractor dynamics for haulage operation

The free body diagram of single axle trailer and tractor for haulage operation on an inclined plane as shown in Fig. 1

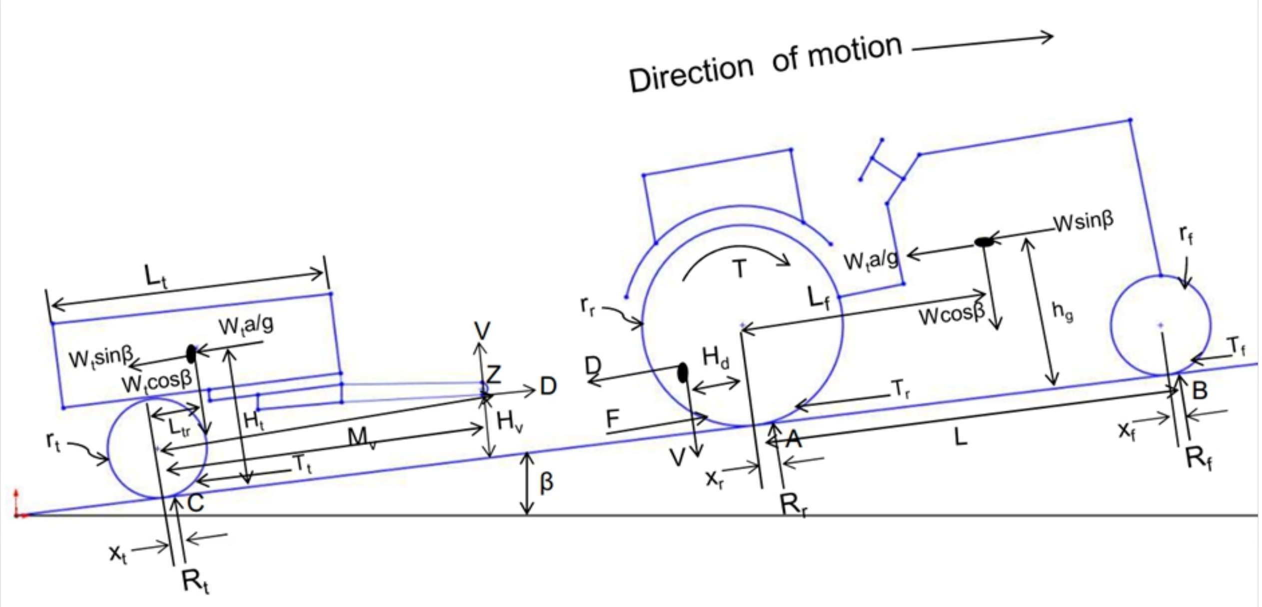


Fig.1: Free body diagram of 2WD tractor and unbalanced trailer on a sloppy surface

Motion of unbalanced trailer in X-Z plane

Force parallel to ground

$$D= W_t \sin\beta + W_t \frac{\mu}{g} + T_t \quad \text{... (1)}$$

Forces perpendicular to ground

$$V= W_t \cos\beta - R_t \quad \text{... (2)}$$

Considering the moment of all the forces about hitch point Z. we get

$$R_t(M_V - X_t) - W_t\cos\beta(M_V - L_{tr}) - W_t(\frac{\alpha}{g}+\sin\beta)(h_t - H_v) + H_t H_v = 0 \quad \text{... (3)}$$

Normal reaction at trailer wheel is given by

$$R_t = \frac{W_t[L_{tr}\cos\beta + (H_v - h_t)(\frac{a}{g} + \sin\beta) - M_v\cos\beta}{p_t(r_t - H_v) - M_v} \quad \text{... (4)}$$

Where,

D = draft force on trailer hitch point

V = vertical force on trailer hitch point

W_t = weight of empty trailer

β = angle of slope inclination

a = acceleration of tractor

g = acceleration due to gravity

T_t = rolling resistance of trailer tires = ρ_t X R_t

R_t = normal soil reaction force on trailer wheel

M_v = horizontal distance between trailer hitch point and center of trailer axle

X_t = eccentricity of trailer wheel

L_{tr} = horizontal distance between C.G and center of trailer axle

H_t = height of trailer C.G from ground surface

H_v = tractor's hitch point height above the ground

L_{tr} = horizontal distance between C.G and center of trailer axle

ρ_t = coefficient of rolling resistance of rear tires of the tractor

r_t = rolling radius of trailer wheel

C.G height of loaded trailer above the ground

The C.G height of loaded trailer above the ground is calculated by assuming that C.G of unloaded trailer lies in the floor of the trailer.

The resultant C.G height of loaded trailer is given by

$$h_t = H_t + \frac{W_p\,(\frac{h_m}{2})}{W_p + W_t} \quad \text{... (5)}$$

The height of C.G of the material on the trailer is assumed to be $\frac{h_m}{2}$

where,

W_p = mass of material on the trailer.

H_t = C.G of empty trailer

W_t = mass of empty trailer

Motion of 2WD tractor in -Z plane (uphill)

Forces parallel to ground

$$F = D + W\frac{\alpha}{g} + W\sin\beta + T_f + T_r \quad \text{... (6)}$$

Forces perpendicular to ground

$$R_f = W\cos\beta - R_r + V \quad \text{... (7)}$$

Taking moment of all forces about the contact point 'B' of front tire with ground, we get

$$R_r = \frac{[W(L+X_f-X_r)\cos\beta + Wh_g(a/g+\sin\beta) + v(H_D+L+X_f) + DH_g]}{L+X_f-X_r} \quad \text{..(8)}$$

where,

F = thrust developed at tire-terrain surface interface

W = weight of the tractor

L = wheel base of tractor

h_g = C.G height of tractor from ground surface

T_f = rolling resistance of the front tires of the tractor = ρ_f X R_f

T_r = rolling resistance of the rear tires of the tractor = ρ_r X R_r

ρ_f = coefficient of rolling resistance of front tires of the tractor

ρ_r = coefficient of rolling resistance of rear tires of the tractor

R_f = normal reaction at front axle of the tractor, and

R_r= normal reaction at rear axle of the tractor

Longitudinal shift of wheel can be determined by

$$e_f = r_f \times MRR_f \quad \text{.. ...(9)}$$

$$e_r = r_r \times MRR_r \quad \text{...(10)}$$

where,

e_f =eccentricity of front wheel

e_r = eccentricity of rear wheel

MRR= motion resistance ratio

r_f = rolling radius of front wheel, and

r_r= rolling radius of rear wheel

Stability index

Stability index is defined as dynamic weight on front axle divided by the total static weight of tractor. For safe haulage operation generally stability index is consider as 20%.

$$ST = \frac{\text{dynamic weight on front axle } (r_r)}{\text{static weight of tractor (w)}} \times 100 \quad \text{... (11)}$$

MATERIALS AND METHODS

The test tractor had technical specifications of 39 kW PTO power, four cylinders, four-stroke, direct injection and water cooled engine. Its high idle speed and rated speed were 2300 rpm and 2150 rpm, respectively. The total gross weight of tractor was 2985 kg. With the tractor level, the weight supported by rear and front axle were 1805 kg and 1185 kg respectively. The wheel base of test tractor was 2120 mm with centre of gravity of 834 mm located ahead of rear axle and centre of gravity of 802mm above ground. The tractor hitch height above the ground was 600 mm and hitch horizontal from axle was 585 mm. The test tractor equipped with single 7.5-16 8 PR bias tire on the front axle and single 16.4- 28 12PR bias tire on the rear axle. The front wheel rolling radius and rear wheel rolling radius were recorded as 394 mm and 686 mm respectively from the tire manufacture hand book. The test tractor was instrumented to measure the draft, horizontal and vertical forces imposed by the trailer at hitch point. All the data were stored in the laptop through a data logger.

Data logger

The SoMat EDAQ was used in study to store data. This is a microprocessor-based data acquisition system designed for portable data collection in a variety of test environments. Input power for the system operates in a wide range from 10 to 55 volts DC for the processor. Internal back-up batteries protect the EDAQ from unplanned power losses or low voltage events. It consists of 32 channels, 16 for bridge and 16 HLS channel to collect the data in different mode as shown in Figure.2.

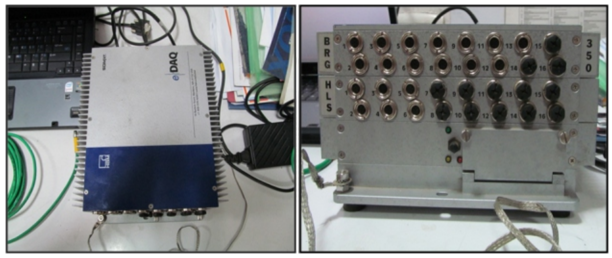


Fig. 2: SoMat EDAQ

Experimental setup for measurement of force at hitch point of tractor

During the haulage operation, there were two forces (horizontal and vertical force) acting at the hitch point of tractor. For measurement of these two forces a new tractor coupling mouth was fabricated. It consists of two load cell. Both load cell had 5 ton capacity. One load cell was used for measuring horizontal force and another was used for measuring the vertical forces as shown in Figure. 3(a) and Figure. 3(b) respectively.

Research Plan

For the experiments a 39 kW PTO power tractor was used for haulage operations. The research plan of haulage operation is listed in Table.1.

Test Procedure

The haulage performance was conducted using test tractor with single axle dual tire trailer on the tar macadam road (Figure.4). The selected tar macadam road was taken 2 km long for the haulage performance test. Other tarmacadam with varying terrain conditions (4 degree uphill and 4 degree downhill slope) was also selected to perform haulage test.

Table1: Haulage performance

Independent parameters	Dependent parameters
Tractor – 39 kW PTO power	Draft, kg
Trailer - Single axle four wheel (unbalanced trailer)	Vertical Force, kg
Rear tire- 16.4- 28 12PR and 1.1kg/cm^2 inflation pressure	Stability Index
Front tire- 7.5-16 8 PR and 2.2 kg/cm^2 inflation pressure	
Pay load- 13000 kg, 14000 kg, 15000 kg and 19000 kg	
Gear- H1, H2, H3, H4 (8.56 – 29 km/h)	
Surface - Tar macadam	

The road was ensured to be obstacle free. A single axle (dual tire) trailer was hitched with single point hitch. Three pay loads of 13000 kg, 14000 kg, 15000 kg and 19000 kg were used for haulage operation. The performance parameter such as draft force and vertical force were measured at different speed of test tractor. The test tractor was run at speed of 8.56 to 29 km/h. Draft force and vertical force acting at hitch point was measured by fabricated tractor coupling mouth with help of two load cells.

RESULTS AND DISCUSSION

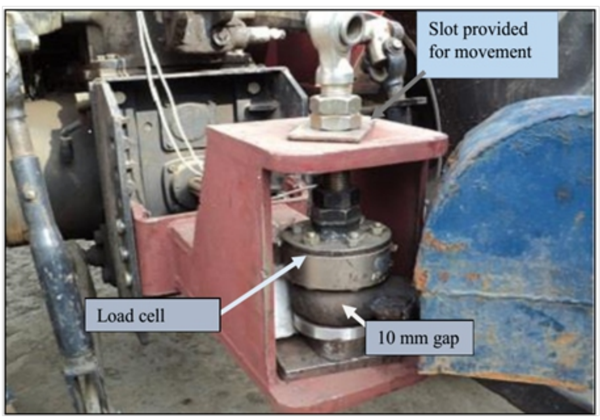
To access the dynamic behavior of 39 kW agricultural tractor for haulage performance for maximum load carrying capacity, a test was conducted on tar macadam surface with varying terrain conditions (normal plane surface, 4 degree uphill and 4 degree downhill slope) using a single axle dual tire trailer with 13000 kg, 14000 kg, 15000 kg and 19000 kg pay loads. The horizontal force and vertical force at single hitch point of tractor were measured with help of fabricated tractor coupling mouth. The dynamic force on the front axle during haulage operation for calculating measured stability index was computed using equation 7.

Haulage Operation on plane surface

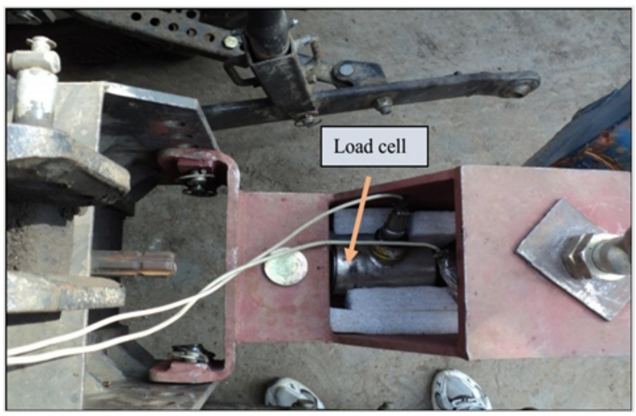
The haulage operation was conducted using test tractor with single axle dual tire trailer on the plane tarmacadam road. The performance parameter such as draft and vertical force measured at single hitch point of tractor with 13000 kg, 14000 kg, 15000 kg and 19000 kg pay loads respectively. Haulage performance of the tractor at varying payloads is shown in Figure 5. The data indicate that the vertical weight transferred from the trailer to the hitch point varies from 1483 kg to 2224 kg. This corresponds to 11.4 % to 11.7 % weight of the trailer gross weight. Also it was noticed that the variation in draft force as 209 kg to 468 kg. These forces were considered to calculate the stability index and plotted in Fig.5 with gross trailer weight. Generally the operation is considered safe if stability index is greater than 20 % (Harbarta, 1971). Based on this consideration the safe maximum haulage carrying capacity of this tractor was 15000 kg. From the Figure.5, the goodness of linearity (R^2 value) for actual vertical force, predicted vertical force, actual draft force and predicted draft force were observed 0.93, 1, 0.92 and 1 respectively. A very good linearity was observed in model of observed stability index (R^2 = 0.98) and predicted stability index (R^2 = 0.99).

Haulage Operation at uphill 4 degree slope

The haulage operation was conducted using test tractor with single axle dual tire trailer on the tarmacadam road with uphill four degree slope. The performance parameter such as draft and vertical force measured at single hitch point of tractor with 13000 kg, 14000 kg, 15000 kg and 19000 kg pay loads respectively. Haulage performance of the tractor at varying payloads at uphill 4 degree slope is shown in Figure 6. The data indicate that the vertical weight transferred from the trailer to the hitch point varies from 1233 kg to 1683 kg. This corresponds to 9.5 % to 8.9 % weight of the trailer gross weight. Also it was noticed that the variation in draft force as from 470 kg to 637 kg. This shows that the weight transferred to hitch point at 4 degree uphill slope is 16.67 % to 23.39 % less than that on plane surface. However the draft force was increased from 17.25 % to 26.47 %. This increase is due to increase in grade resistance by 4 degree slope. Based on the desired stability index of 20 % the safe maximum haulage carrying capacity of this tractor on 4 degree slope was observed as 13000 kg. From the Figure.6, the goodness of linearity (R^2 value) for actual vertical force, predicted vertical force, actual draft force and predicted draft force were observed 0.53, 0.98, 0.99 and 0.99 respectively. A



(a)



(b)

Fig.3: Experimental set up used for measuring (a) vertical force at hitch point (b) measuring horizontal force at hitch point

Fig.4: Haulage operation on tarmacadam surface

good linearity was observed in model of observed stability index (R^2 = 0.98) and predicted stability index (R^2 = 0.99).

Operation at down the hill 4 degree slope

The haulage operation was conducted using test tractor with single axle dual tire trailer on the tarmacadam road with downhill four degree slope. The performance parameter such as draft and vertical force measured at single hitch point of tractor with 13000 kg, 14000 kg, 15000 kg and 19000 kg pay loads respectively. Haulage performance of the tractor at varying payloads at downhill 4 degree slope is shown in Figure. 7. During the downhill trailer exerted a thrust force on the tractor hitch point. This thrust forces was equal to grade resistance force minus rolling resistance force. The data indicate that the vertical weight transferred from the trailer to the hitch point varies from 1787 kg to 2561 kg. This corresponds to 13.7 % to 13.4 % weight of the trailer gross weight. Also it was noticed that the variation in thrust force as 156 kg to 360 kg. Based on the desired stability index of 20% the safe maximum haulage carrying capacity of this tractor was observed as14500 kg. From the Figure.7, the goodness of linearity (R^2 value) for actual vertical force, predicted vertical force, actual draft force and predicted draft force were observed 0.97, 0.99, 0.97 and 0.99 respectively. A very good linearity was observed in model of observed stability index (R^2 = 0.98) and predicted stability index (R^2 = 0.98).

Validation of the predicated haulage performance with experimental results

The haulage performance in terms of draft, vertical force transferred at single hitch point and stability index was calculated using equations 1 to 11 as explained in section 2. These values were validated with experimental results as shown in Table.2. The results indicate that the predicated stability index values are 4 % to 33 % higher than the experimental values on 4 degree uphill and downhill slopes. However on plane surface the variation is within 12 %.

$$\% \text{ variation *} = \frac{\text{actual - predicated}}{\text{actual}} \text{x } 100$$

CONCLUSION

The experiment was conducted on tar macadam surface of varying terrain conditions (normal plane surface, 4 degree uphill and 4 degree downhill slope) with a single axle dual tires trailer to accommodate different payloads for haulage performance. The payload was varied from 13000 to 19000 kg in the trailer. Performance parameters, mainly draft forces and vertical forces were measured at operating speed. Following conclusions were drawn from

Table 2: Variation between actual and predicated vales

Operating surface	Draft force (kg)			Vertical force (kg)			Stability index %		
	Predicated	Actual	% variation*	Predicated	Actual	% variation*	Predicated	Actual	% variation*
Plane surface									
13 tons	278	210	-32.38	1398	1482	5.67	22.3	22.6	1.50
14 tons	299	209	-43.06	1506	1584	4.92	21.47	22.1	2.81
15 tons	321	218	-47.25	1614	1892	14.69	20.2	19.5	-3.48
19 tons	406	468	13.25	2044	2224	8.09	15.31	13.7	-11.67
4 degree uphill									
13 tons	370	470	21.28	1235	1233	-0.16	20.65	19.8	-4.35
14 tons	398	505	21.19	1315	1405	6.41	19.63	18.2	-7.86
15 tons	425	536	20.71	1386	1727	19.75	18.68	15.2	-22.57
19 tons	530	637	16.80	1580	1683	6.12	13.69	10.4	-31.89
4 degree downhill									
13 tons	163	156	-4.49	1554	1787	13.04	24.86	22.8	-8.99
14 tons	174	210	17.14	1689	2011	16.01	23.47	20.2	-16.19
15 tons	184	256	28.13	1832	2156	15.03	22.01	19.3	-13.92
19 tons	217	360	39.72	2498	2561	2.46	18.69	14	-33.31

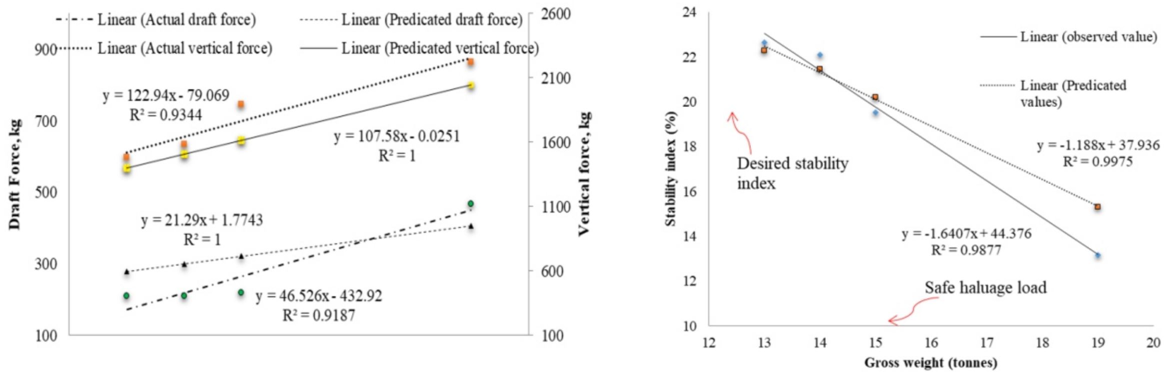


Figure.5: Haulage performance on plane surface

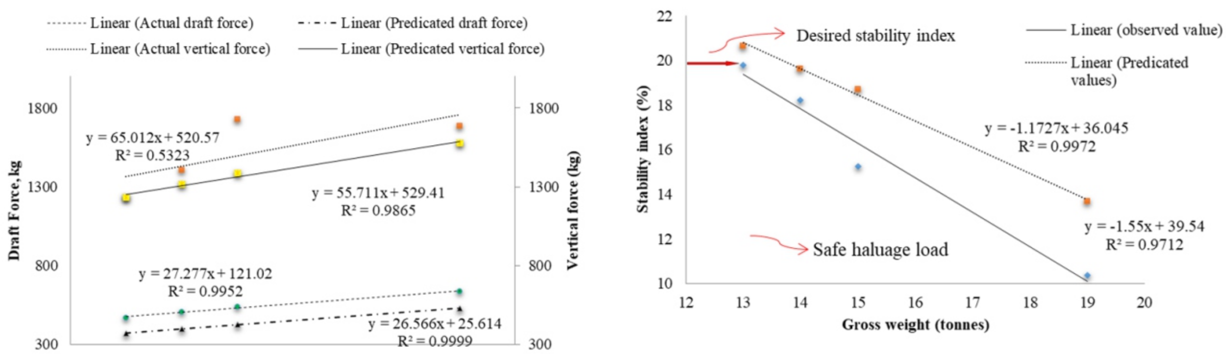


Figure.6: Haulage performance on uphill 4 degree slope

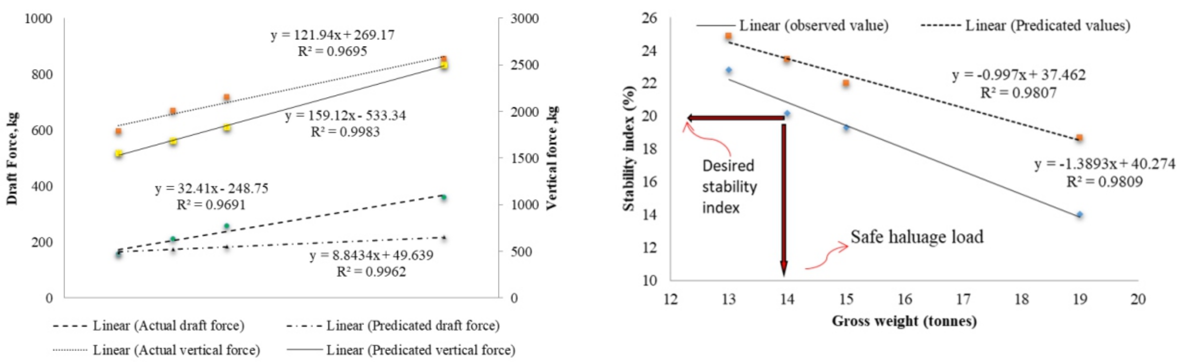


Figure.7: Haulage performance on downhill 4 degree slope

above study.

1. The R^2 value for actual vertical force, predicted vertical force, actual draft force and predicted draft force were observed 0.93, 1, 0.92 and 1 respectively. A very good linearity was observed in model of observed stability index (R^2 = 0.98) and predicted stability index (R^2 = 0.99) during haulage operation at plane surface.

2. The (R^2 value) for actual vertical force, predicted vertical force, actual draft force and predicted draft force were observed 0.53, 0.98, 0.99 and 0.99 respectively. A good linearity was observed in model of observed stability index (R^2 = 0.98) and predicted stability index (R^2 = 0.99) during haulage operation at four degree uphill slope.

3. The R^2 value for actual vertical force, predicted vertical force, actual draft force and predicted draft force were observed 0.97, 0.99, 0.97 and 0.99 respectively. A very good linearity was observed in model of observed stability

index ($R^2 = 0.98$) and predicted stability index ($R^2 = 0.98$).

4. Based on the desired stability index of 20%, the safe maximum carrying capacity of this tractor on plane surface was found to be 15000 kg. However, on 4 degree uphill and 4 degree downhill slopes the loading capacity was selected to 13000 kg and 14000 kg respectively.

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