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Research paper

Importance of automatic variable single hitch point for 2WD tractors – A theoretical analysis

P.K. Pranav*, T. Tapang, A. Pal, S.K. Deb

Department of Agricultural Engineering, North Eastern Regional Institute of Science and Technology, Nirjuli, Itanagar 791109, India

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ABSTRACT

Software is developed in Visual Basic 6 environment for predicting the haulage performance of 2WD tractor. Three types of inputs namely tractor, trailer and operating parameters are required to run the software. Various empirical and theoretical equations were used for predicting the haulage performance parameters such as draft, slip, actual speed, transport productivity, transport efficiency, fuel economy index, front and rear wheel utilization factor etc. In addition to this, the software also gives a warning signal when either stability of tractor or engine power fails. It was used to evaluate the haulage performance by varying the hitch height (HH) at various operating conditions. It was observed that there is a significant increase in the maximum payload 78, 300 and 3300% while HH was lowered from 0.7 to 0.1 m at 0, 5 and 10° slope, respectively. However, the dynamic load on rear axle increased from 1470 to 1730 and 1500 to 1820 kg when HH increased from 0.1 to 0.7 m at 800 and 1000 kg payload, respectively. Further, it was observed that fuel economy index was reduced by 6.3% and engine power requirement by 4.23% at 800 kg payload when HH was raised from 0.1 to 0.7 m. It was observed that stability of tractor increases by lowering the HH, however, traction increases by raising the same. Hence, it was concluded that variable HH can meet the requirements of stability as well as traction during transport as per necessity.

1. Introduction

Production and sale of tractors in India have increased considerably during the last two decades. The use of tractor is increasing not to perform field operations only but also for transport work. Due to poor road conditions in rural India, the transportation of commodities through tractor–trailer system is well accepted. According to an estimate, 70 per cent of the use of tractors is related to haulage operations (Kumar, 1994). The basic design of the tractor is for field operation and very little attention is paid for the requirements of the haulage work which results in poor performance and fatal accidents in many cases. Tractor accidents are estimated to claim many lives annually out of which approximately 70 percent are caused by either overturning sideways or rearward. Moreover, according to National Safety Council (1968) rearward overturning is more fatal than the sideways overturning. Rearward overturning takes place when dynamic front wheel reaction is reduced to zero. Weight transfer from front to rear takes place due to moment generated by position of applied pull about the ground contact point of rear wheel. Rearward overturn occurs mainly due to steep-up slope and rear wheel obstructed from rotating which is very frequent in rural and hilly areas. Habarta (1971) analyzed the problem and reported that regardless of the load of the tractor, the weight on the front wheels should not be less than 20% of the weight of the tractor.

There are three limiting factors (i) lateral stability (ii) traction and (iii) engine power for the maximum pull during haulage operation. The prediction of haulage performance of tractor and power tiller is the prime area of study for many scientists (Sahay and Tewari, 2004; Sahu and Pandey, 2005; Kumar and Pandey, 2009; Pranav et al., 2012) from last decades but none of them quantify the effect of hitch height on haulage performance. However, Pal and Deb (2009) found that stability and traction significantly depends upon hitch height during haulage operation. The lowered hitch height increases the tractor stability due to lower weight transfer from front to rear axle but at the same time sacrifices tractive ability. Tractive ability and stability both are important for design engineers. In one hand, higher tractor ability enhances

* Corresponding author.
E-mail addresses: pkpv@nerist.ac.in, pkjha78@gmail.com (P.K. Pranav).

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the tractor performance such as fuel economy index, transport efficiency etc., but in other hand stability fails which results in accidents. To overcome this problem, tractor manufacturers have provided variable hitch heights (Fig. 1) which is practically not feasible for an operator to change as per frequent need. In this condition, most of the time tractor runs either sacrificing the stability or traction. An automatic adjustable hitch point may solve the problem which will adjust the height according to the need of either stability or traction. Keeping this in mind, a study has been formulated to theoretically analyze the advantages of automatic variable hitch height for haulage operations in 2WD tractor with following specific objectives:

i. To developed a computer program in Visual Basic for predicting haulage performance of 2WD tractors and
ii. To analyze the importance of variable hitch height during haulage operation.

2. Theoretical considerations

This section describes parameters needed to calculate the haulage performance

2.1. Pull force

The horizontal and vertical component of force required to pull a load is known as draft and vertical force, which can be calculated by equating the horizontal and vertical components forces as shown in Fig. 2, respectively.

$$D = Wt \times \sin(\alpha) + \left(Wt \times \frac{a}{g}\right) + (R_t \times st) \quad (1)$$

$$V = Wt \times \cos(\alpha) - R_t \quad (2)$$

where,

D = draft, kg
V = vertical force, kg
Wt = weight of loaded trailer, kg
α = slope, °
a = acceleration of the tractor, m/s^2
g = acceleration due to gravity, m/s^2

Fig. 1. Manual variable hitch height in existing tractors.

R_t = reaction at trailer wheel, kg
st = coefficient of rolling resistance

2.2. Rolling radius (RR)

Rolling radius of wheel is defined as the distance covered by wheel in one revolution divided by 2π. The rolling radius is calculated by imperial equation (Brixius, 1987).

$$RR = \frac{2.5 \times \frac{od}{2} \times slr}{1.5 \times \frac{od}{2} + slr} \quad (3)$$

where,

od = overall diameter, m $= 1.06 \times rd + 2 \times sh$
slr = static loaded radius, m $= \frac{od}{2} - \delta \times sh$
sh = section height, m $= 0.75 \times sb$
sb = section width, m
rd = rim diameter, m
δ = Deflection, fraction

2.3. Coefficient of rolling resistance (CRR)

It is the ratio of rolling resistance per unit normal load which is calculated by imperial equation (Brixius, 1987).

$$CRR = \frac{1}{Bn} + 0.04 + \frac{0.5 \times S}{\sqrt{Bn}} \quad (4)$$

where,

S = wheel slip, decimal
Bn = Mobility Number $= \frac{CI \times sb \times od}{R_r} \times \left(\frac{1 + 5 \times \frac{\delta}{sh}}{1 + 3 \times \frac{sb}{od}}\right)$
CI = cone index, kPa
R_r = Reaction at rear wheel, kg

2.4. Eccentricity (X)

Eccentricity is defined as the deviation of centre of wheel with the point of application of wheel reaction in dynamic condition. It is derived from the mechanics of wheel

$$X = RR \times CRR \quad (5)$$

2.5. Gross traction ratio (GTR)

Gross traction ratio is defined as the ratio of gross tractive force to the dynamic weight on the driving wheel and it is expressed as (Brixius, 1987):

$$GTR = 0.88 \times \left(1 - e^{-0.1 \times Bn}\right) \times \left(1 - e^{-7.5 \times S}\right) + 0.04 \quad (6)$$

2.6. Net traction ratio (NRT)

$$NTR = GTR - CRR \text{ and} \quad (7)$$

$$NTR = \frac{D}{R_r} \quad (8)$$

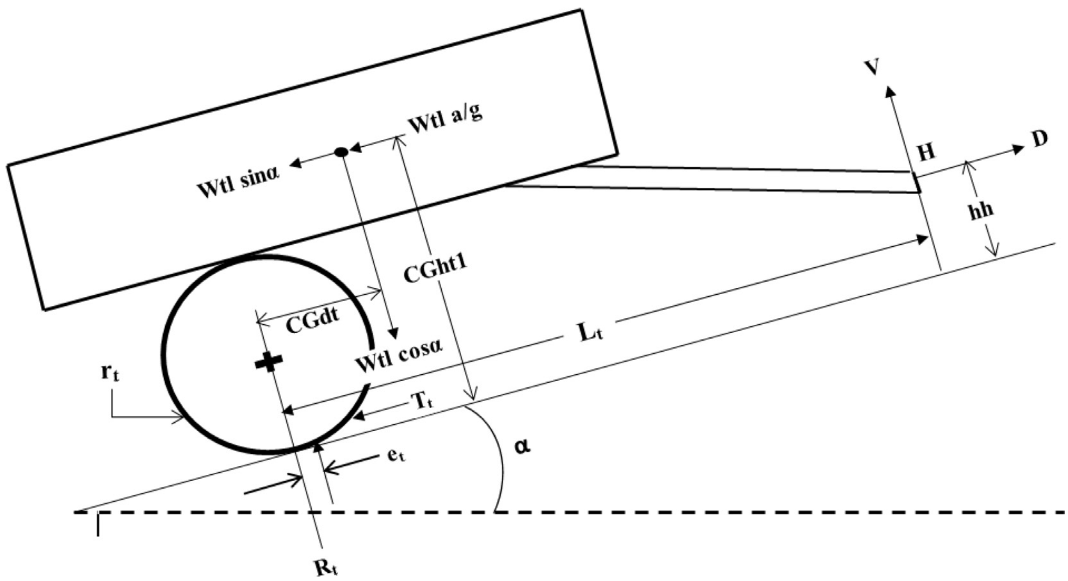


Fig. 2. Free body diagram of unbalanced trailer.

2.7. Reaction at wheels

Dynamic forces acting on unbalanced trailer is shown in Fig. 2. The reaction at trailer wheel was calculated by taking the moment about hitch point H considering equilibrium condition. Further, the dynamic force analysis of 2WD tractor is shown in Fig. 3. The wheel reaction of front and rear wheels was calculated through force analysis for equilibrium condition which are as follows:

$$R_t = \frac{Wtl \times \left(CGdt \times \cos\alpha + (hh - cght1) \times \left(\frac{a}{g} + \sin\alpha\right) - Lt \times \cos\alpha\right)}{st \times (rt - hh) - Lt} \tag{9}$$

$$R_f = \frac{W \times \cos\alpha \times (CGd - e_r) - W \times \left(\frac{a}{g} + \sin\alpha\right) - (D \times hh) - (V \times hd)}{wb + e_f} \tag{10}$$

$$Rr = \frac{W \times (wb + er - CGd) \times \cos\alpha + W \times (hh + hg) \times \left(\frac{a}{g} + \sin\alpha\right) + V \times (Hd + wb + er) + (D \times hh)}{W + ef - er} \tag{11}$$

where,

R_f = Reaction force at front wheel, kg
cgdt = CG distance from trailer wheel axis, m
Lt = Distance between hitch point and center of trailer wheel, m
cght1 = CG height of the loaded trailer, m
ef = Eccentricity of the front wheel, m
er = Eccentricity of the rear wheel, m
et = Eccentricity of the trailer wheel, m
CGd = CG distance of the tractor from the rear axle, m
hd = Hitch distance from rear axle, m
wb = Wheel base of the tractor, m
W = Total weight of the tractor, kg
Hh = Hitch height from the ground, m
hg = CG height of the tractor from hitch height, m

2.8. Wheel utilization factor (K)

The wheel utilization factor is the ratio of dynamic weight of the axle to the total static weight of tractor. The front and rear wheel utilization factor can be calculated as follows:

$$K_f = \frac{R_f}{W};\ \ K_r = \frac{R_r}{W} \tag{12}$$

2.9. Actual engine power required

The engine power utilized depends upon the load on the trailer, surface type, gear selection etc. The actual engine power required (AEPR) is the ratio of axle power to the transmission efficiency between the engine and axle.

$$AEPR = \frac{\text{Axle power}}{\text{Tractive Efficiency}} \tag{13}$$

2.10. Transport productivity (TrP)

The transport productivity is defined as the product of payload transported and the average forward speed which is calculated as follows:

$$TrP = \text{Payload} \times \text{speed} \tag{14}$$

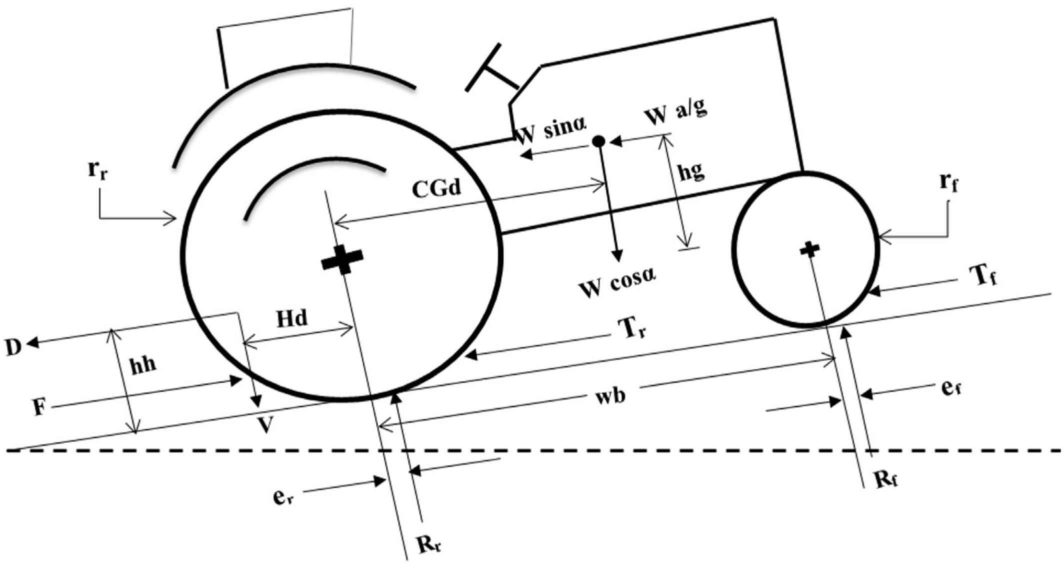


Fig. 3. Free body diagram of tractor.

2.11. Transport efficiency (TrE)

Transport efficiency is the ratio of transport productivity to the actual engine power required. Calculation of the transport efficiency is as follows:

$$\mathrm{TrE} = \frac{\mathrm{TrP}}{\mathrm{AEPR}} \tag{15}$$

2.12. Fuel economy index (FEI)

Fuel Economy Index is the amount of fuel consumed per unit payload over a unit distance. It is expressed as L/ton-km.

$$\mathrm{FEI} = \frac{\mathrm{SFC} \times \mathrm{AEPR}}{\mathrm{TrP}} \tag{16}$$

3. Development of software

The software was developed in Visual Basic 6 environment for predicting the haulage performance of 2WD tractor at various operating conditions. Three types of inputs namely tractor, trailer and operating parameters are required to run the software. The tractor parameters mainly include total static weight, weight distribution on front and rear axle, wheel base, front and rear tyre size, engine power etc. Similarly, trailer parameters contain trailer dimensions, tyre size and hitch point location. Further, operating parameters comprise payload, road slope, surface type, acceleration, travel speed etc. Draft and vertical force play an important role in predicting the haulage performance parameters which was calculated using Eqs. (1) and (2), respectively. The dynamic wheel reactions were estimated using force analysis of tractor-trailer system (Eqs. (9)–(11)). Brixius (1987) equations were used to calculate rolling radius (Eq. (3)), motion resistance ratio (Eq. (4)), eccentricity (Eq. (5)), gross traction ratio (Eq. (6)) and net traction ratio (Eqs. (7) and (8)). Wheel slip was calculated using iteration process with initial value of 0.1 percent and with an increment of 0.1 percent (Pranav and Pandey, 2008). Finally, software calculates the haulage performance parameters such as draft, slip, actual speed, transport productivity (Eq. (14)), transport efficiency (Eq. (15)), fuel economy index (Eq. (16)), front and rear wheel utilization factor (Eq. (12)), engine power required (Eq. (13)) etc. The sequence of calculation and iteration process of the developed software is given in a flow chart which is shown in Fig. 4. In addition to this, software also gives a warning signal when either stability or engine power fails. Stability warning signal appears when dynamic weight on front axle is less than 20% of the total static weight of the tractor. The software was run to generate the performance parameter for various hitch height to analyze the effect of the same. The software has mainly two windows, one has tractor and trailer related input parameters (Fig. 5) and another has input for to operating parameters and output (Fig. 6).

4. Results and discussion

4.1. Prediction of haulage performance

The developed software was used to predict the haulage performance of a test tractor with a two wheel trailer for various operating conditions. The required input parameters namely, tractor, trailer and operating parameters are given in Table 1. The output of the software is haulage performance parameter such as draft (D) transport productivity (TrP), transport efficiency (TrE), drawbar power (DP) etc. which is given in Table 2. It was observed that the software predicted performance parameters were very close to the parameters predicted by Sahu and Pandey (2005), Kumar and Pandey (2009) and Pal and Deb (2009) as same empirical equations were used to predict the performance parameters in this software. Therefore, the developed software was used to analysis the effect of hitch height on tractor performance and their stability.

4.2. Effects in lowering hitch height

Lowering the hitch height (HH) is advantageous when lateral stability fails. Generally, maximum payload is limited due to stability in case of 2WD tractors. In a nutshell, it can be explained that lowering the HH is helpful in increasing maximum payload as well

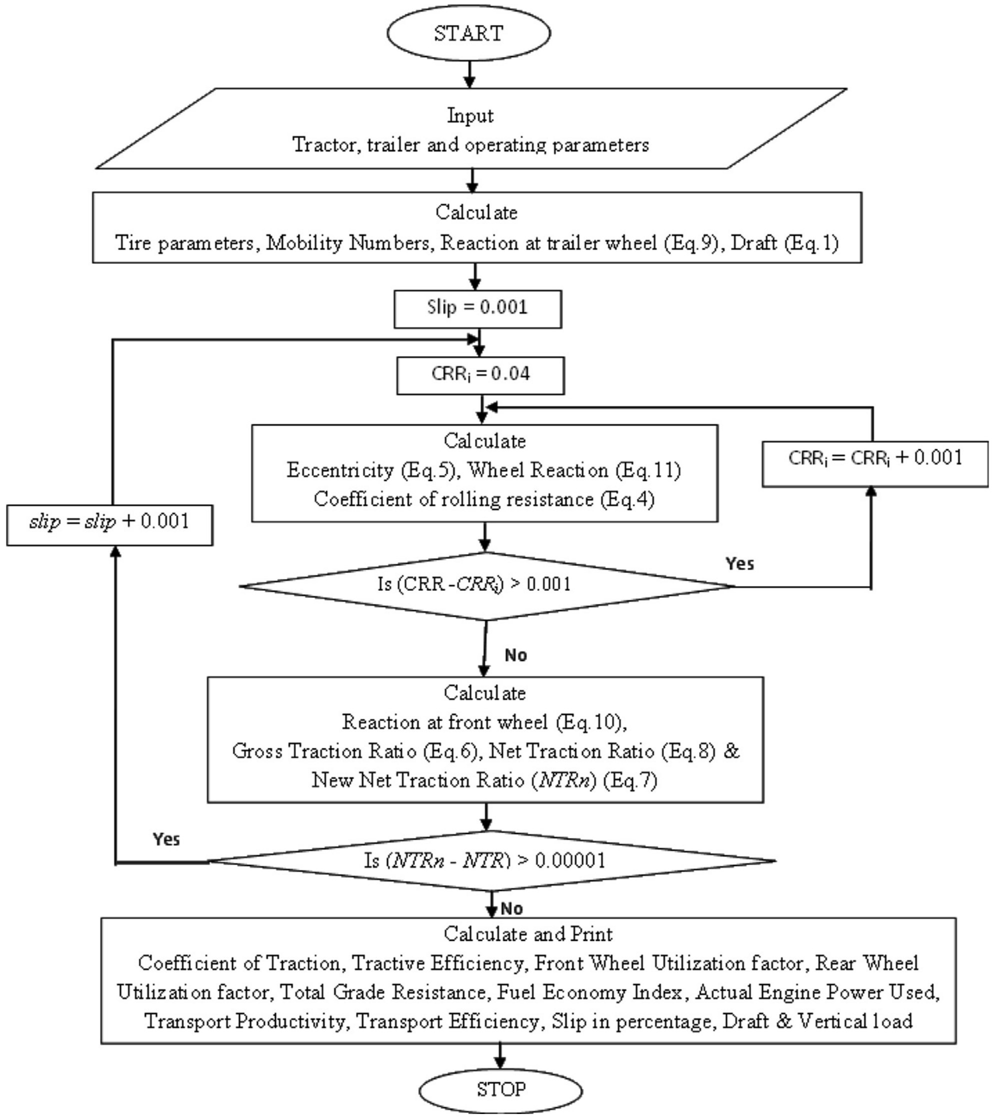


Fig. 4. Flow chart of the developed software.

as in climbing higher slope by sacrificing little amount of fuel consumption (Tage, 2014).

4.2.1. Effect on maximum pay load

It was observed that maximum pay load is limited due to stability of tractor on concrete surface. The effect of HH on maximum pay load is shown in Fig. 7 at tarmacadam as well as on kachcha surfaces. From figure, it is revealed that maximum pay load increased when HH reduced for all the slopes and surfaces by maintaining the required stability criteria. It was calculated that maximum payload increased by 78, 300 and 3300% while HH lowered from 0.7 to 0.1 m at 0, 5 and 10° slope on tarmacadam surface, respectively. Due to substantial increased in payload, transport productivity (TrP) also increased significantly (Fig. 8). It is intended that, TrP is enhanced by approximately 14, 18 and 14 ton-km/h at tarmacadam surface for 0, 5 and 10° slopes, respectively. Similar trend was observed on kachcha road also.

4.2.2. Effect on slope

It was observed that maximum pay load for a test tractor is 4200 kg on concrete surface and level ground at 0.5 m HH as longitudinal stability fails beyond this point. The advantage of lowering hitch height on slope is shown in Fig. 9. It was calculated that same tractor can climb up to 8° slope by reducing HH from 0.5 to 0.1 m maintaining the stability criteria. This is the substantial advantage of variable HH to climb up certain slope without stability failure which is frequently required during transport. Further, trial was made for 3000 kg and 2000 kg payloads. The maximum slope on which the test tractor was able to operate was increased from 2 to 11° and 4 to 13°, respectively, on lowering the hitch height from 0.5 m to 0.1 m. Similar, calculation was made for kachcha road also. The maximum slope on which the tractor could traverse was 0 to 9, 1 to 11 and 3 to 12° when the hitch height was lowered from 0.5 m to 0.1 m for 2800, 2300 and 1800 kg payload, respectively.

4.3. Effect of increasing HH

When dynamic load on the front axle is more than 20% of total tractor static weight, it implies less load transfer from front and hence fewer traction efforts. Excess load on front axle create extra rolling resistance. This results in more fuel consumption,

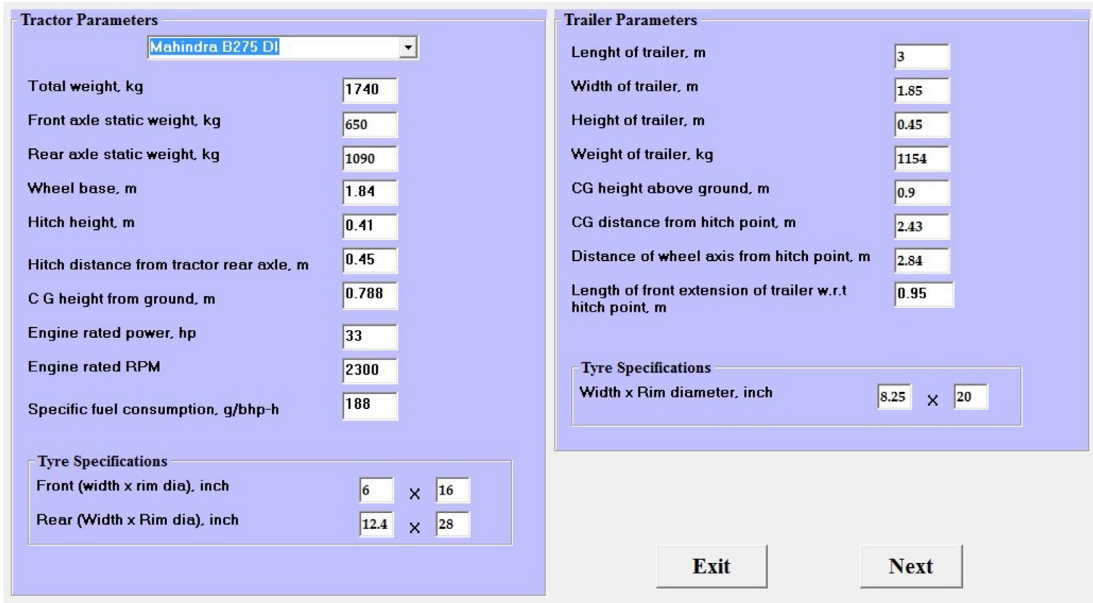


Fig. 5. Window for tractor and trailer input parameters.

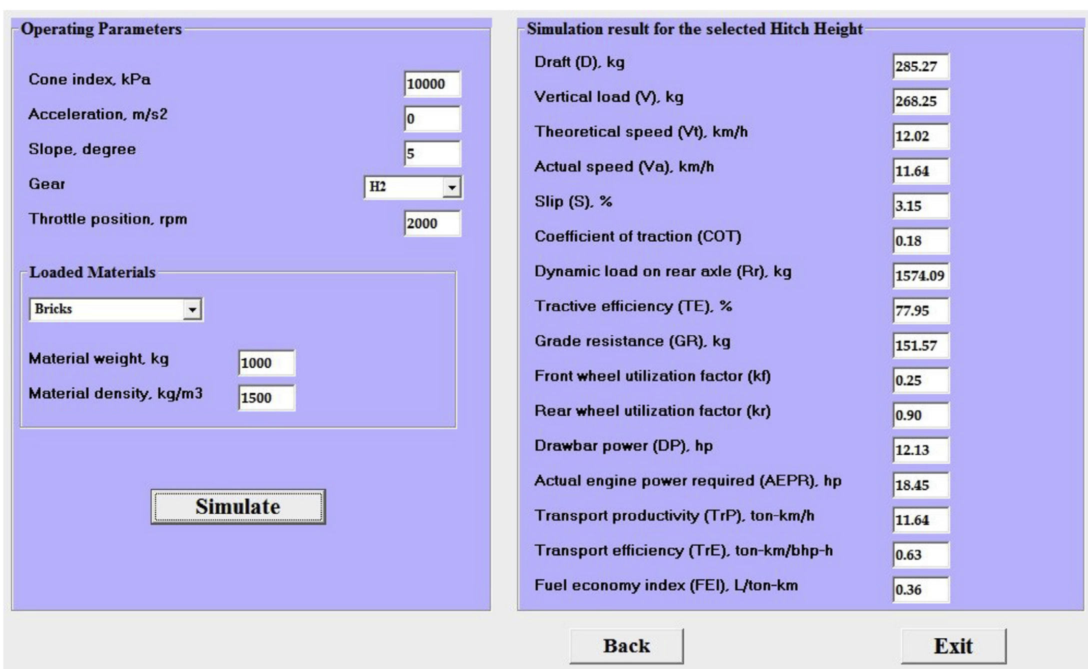


Fig. 6. Window for operational parameter input and output.

higher slips and lower actual speed. To improve tractor performance, HH can be raised to achieve more dynamic load on the rear axle. The advantages of raising HH are supported by software generated outputs which are discussed under the following subsections.

4.3.1. Dynamic load on rear axle

The effect of HH on dynamic load and wheel slip for 800 and 1000 kg payload is shown in Fig. 10. This indicates that dynamic load increased as HH increased for both payload conditions. The dynamic load increased from 1470 to 1730 and 1500 to 1820 kg on increasing the HH from 0.1 to 0.7 m at 800 and 1000 kg payload, respectively while operating on loose soil of cone index value 500 kPa operating at the speed of 4.14 km/h. Also, wheel slip was found to reduce by 1.72 and 2.94% when HH was increased from 0.1 to 0.7 m for 800 and 1000 kg payload, respectively. The basic reason behind these effects is higher weight transfer from the front to the rear axle. It is because of the moment created by horizontal component of draft with respect to contact point of rear wheel which is more in case of higher HH above the ground.

Table 1
Input parameters for the developed software.

Tractor		Trailer		Operating	
Front wheel static weight, kg	650	Length of the trailer, m	3	Road	Tarmacadam
Rear wheel static weight, kg	1090	Width of the trailer, m	1.85	Slope, °	0 and 5
Wheel base, m	1.84	Height of the trailer, m	0.45	Payload, kg	1000, 1500 and 2000
Hitch distance from rear axle, m	0.45	Weight of trailer, kg	1154	Gear	H2 and H3
CG height from ground, m	0.788	CG distance from hitch point, m	5	Operating engine rpm	2000
Hitch height, m	0.41	CG height from ground, m	0.9	Material type	Bricks
Engine power (rated), hp	33	Distance from wheel axis to hitch point, m	2.84	Density of material, kg/m^3	1500
Specific fuel consumption, g/bhp-h	188	Length of front extension of trailer w.r.t hitch point, m	0.95		
Tyre size (front wheel), inch	6 × 16	Tyre size, inch	8 × 20		
Tyre size (rear wheel), inch	12.4 × 28	Trailer weight, kg	1154		

Table 2
Output parameters of the developed software.

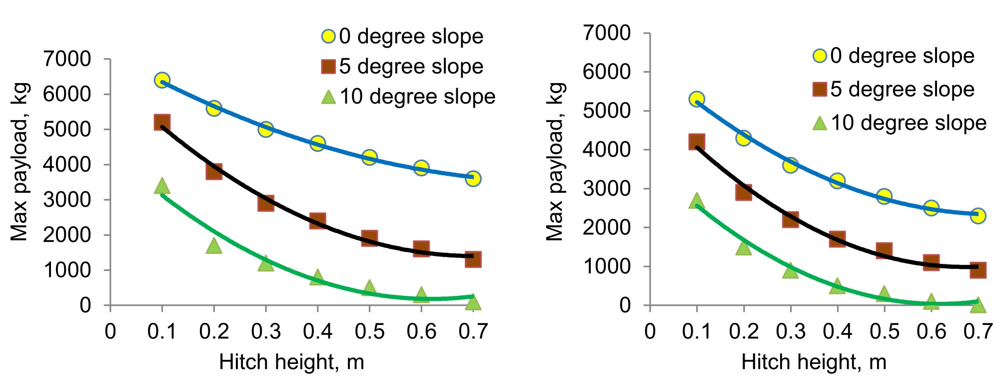
Input Parameters			Output Parameters														
Payload, kg	Slope, °	Vt, km/h	Draft, kg	Lv, kg	Va, km/h	Slip, %	COT	DL, kg	TE, %	GR, kg	kf	Kr	DP, hp	AEPR, hp	TrP, ton-km/h	TrE, ton-km/bhp-h	FEI, L/ton-km
1000	0	12	96.22	303.67	11.89	1.05	0.06	1514	58.94	0.00	0.3	0.87	4.18	9.19	11.89	1.29	0.17
		17	96.22	303.67	16.87	1.05	0.06	1514	58.94	0.00	0.3	0.87	5.93	13.03	16.87	1.29	0.17
	5	12	285.27	268.25	11.64	3.15	0.18	1574	77.95	151.57	0.25	0.9	12.13	18.45	11.64	0.63	0.36
		17	285.27	268.25	16.52	3.15	0.18	1574	77.95	151.57	0.25	0.9	17.22	26.18	16.52	0.63	0.36
1500	0	12	125.5	372.26	11.86	1.31	0.08	1608	62.93	0.00	0.29	0.92	5.44	10.86	17.79	1.64	0.14
		17	125.5	372.26	16.83	1.31	0.08	1608	62.93	0.00	0.29	0.92	7.72	15.41	25.24	1.64	0.14
	5	12	358.64	326.74	11.56	3.83	0.22	1664	79.97	151.57	0.23	0.96	15.15	22.22	17.34	0.78	0.29
		17	358.64	326.74	16.4	3.83	0.22	1664	79.97	151.57	0.23	0.96	21.49	31.53	24.60	0.78	0.29
2000	0	12	157.37	440.76	11.83	1.55	0.09	1702	66.64	0.00	0.27	0.98	6.8	12.56	23.66	1.88	0.12
		17	157.37	440.76	16.79	1.55	0.09	1702	66.64	0.00	0.27	0.98	9.65	17.82	33.58	1.88	0.12
	5	12	434.7	384.3	11.47	4.52	0.25	1754	80.72	151.57	0.21	1.01	18.23	26.19	22.95	0.88	0.26
		17	434.7	384.3	16.28	4.52	0.25	1754	80.72	151.57	0.21	1.01	25.86	37.16	32.56	0.88	0.26

4.3.2. *Fuel economy index and engine power requirement*

The effect of increased HH on fuel economy index (FEI) and actual engine power requirement (AEPR) is given in Fig. 11 for two different payloads of 800 and 1000 kg, at 500 CI and 4.14 km/h speed. It is clear from the figure that FEI reduced from 0.95 to 0.89 L/ton-km and AEPR from 12.29 to 11.77 hp at 800 kg payload when HH was raised from 0.1 to 0.7 m. Similarly, FEI and AEPR also reduced 7.7 and 4.3%, respectively, at 1000 kg payload when HH was increased from 0.1 to 0.7 m. Thus, software generated data revealed that raising the HH above the ground is beneficial in many aspects when traction is limited and sufficient stability is maintained.

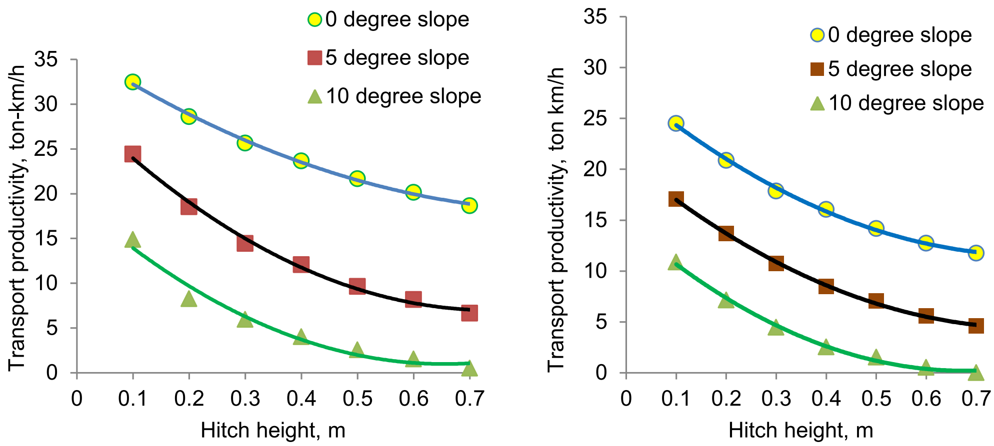
5. Conclusions

A Software in Visual Basic environment was successfully developed to predict the haulage performance of 2WD tractor. A substantial increase in maximum payload, slope traversing capacity and stability were observed in lowering the hitch height. Further, when performance is limited by traction and stability is intact, HH can be raised to obtain higher tractive advantages such as lower fuel economy index and lower engine power requirement. Finally it can be concluded that added haulage performance can be achieved by making an auto variable hitch point in vertical direction to satisfy stability as well as traction criteria.



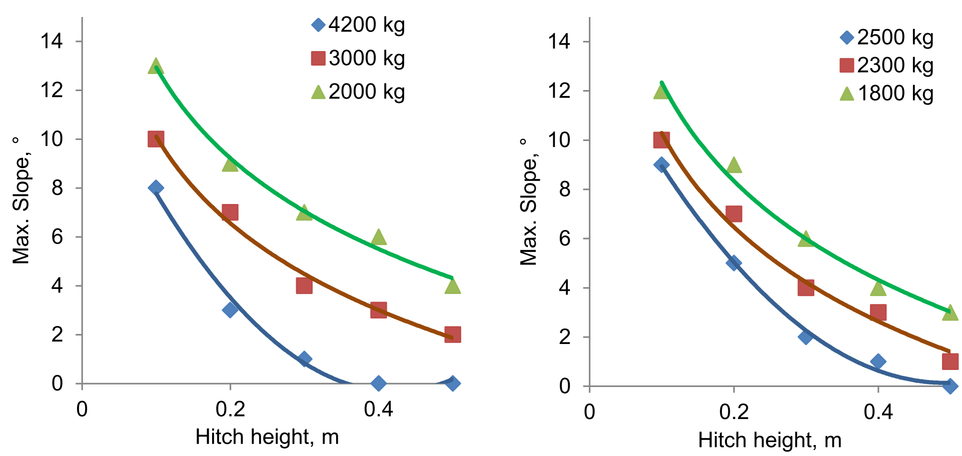
(a) Tarmacadam road (CI>10000 kPa) (b) Kachcha road (CI = 2500 kPa)

Fig. 7. Effect of hitch height on maximum payload.



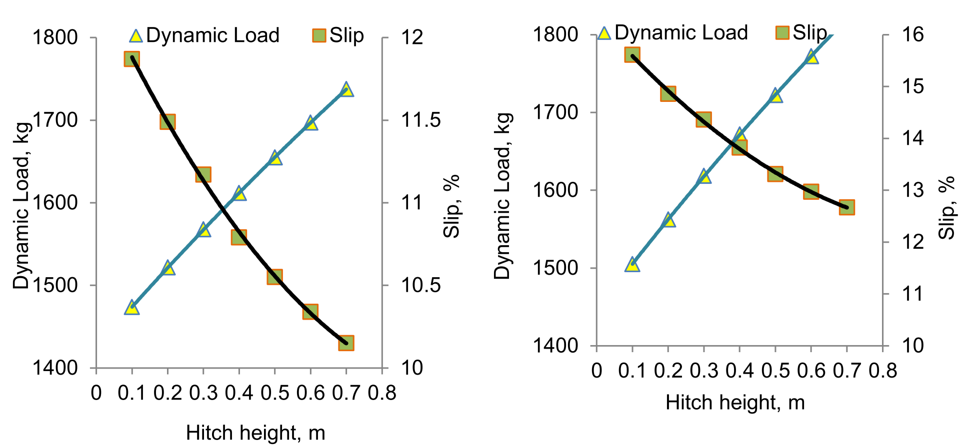
(c) Tarmacadam road (CI>10000 kPa) (d) Kachcha road (CI =2500 kPa)

Fig. 8. Effect of hitch height on transport productivity.



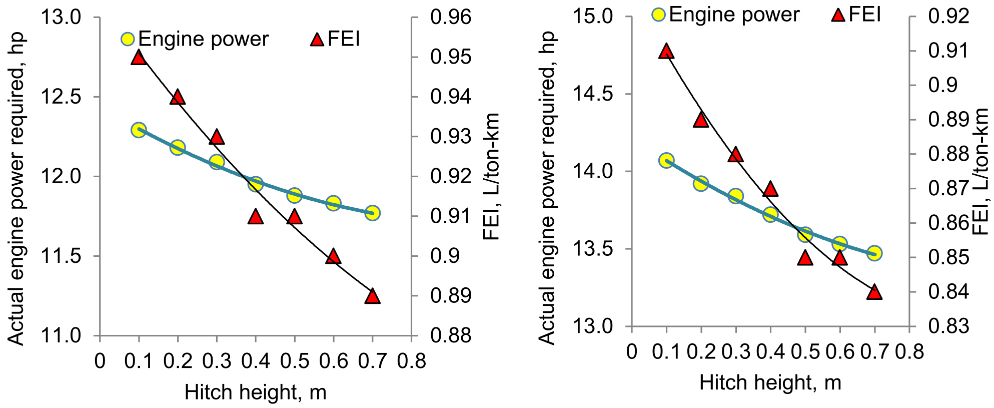
(a) Tarmacadam road (CI>10000 kPa) (b) Kachcha road (CI =2500 kPa)

Fig. 9. Effect of lowering hitch height on slope.



(a) at 800 kg payload (b) at 1000 kg payload

Fig. 10. Effect of HH on dynamic load on rear axle.



(c) at 800 kg payload (d) at 1000 kg payload

Fig. 11. Effect of increasing HH on FEI and engine power requirement.

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