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RESEARCHARTICLE

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Effect of hitch distance on haulage performance for 2WD tractors: A theoretical analysis

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Abstract

Aim of study: A computer program was developed in Visual Basic 10 environment for predicting the haulage performance of 2WD tractors using various empirical and theoretical equations.

Methodology: Three types of inputs related to tractor, trailer and operating parameters were used to calculate the performance parameters through empirical and theoretical equations. The performance parameters included mainly draft, slip, transport efficiency, transport productivity, fuel economy index, rear and front axle dynamic weight, etc. The program was used to evaluate the haulage performance by varying hitch distance (HD) at various operating conditions.

Main results: On one hand lower HD was beneficial in increasing the maximum payload, transport productivity as well as the maximum slope; but at the same time, it reduced the rear axle dynamic load, fuel economy index and actual engine power requirement.

Research highlights: There was a markable effect of HD over tractor performance which can play a role to optimize traction and stability.

Additional key words: computer program; single hitch point; transport productivity; fuel economy index

Abbreviations used: BrixMob (brixius mobility number); CG (centre of gravity); CI (cone index); Coeff (coefficient); Dia (diameter); FEI (fuel economy index); GBL_g (global acceleration due to gravity); HD (hitch distance); Ht (height); Pt (point); Pwr (power); Rad (radian); Sec (Section); TrP (transport prouctivity); WD (wheel drive); Wt (weight)

Authors' contributions: Development of computer program and preparation of manuscript: SK. Testing of the developed program and analysis of output: PKP. Guidance in computer program development: AP. All authors read and approved the final manuscript.

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Introduction

Tractor is a well-accepted power source for agricultural activities as well as for transport deeds in rural areas. Tractors have two main power outlets, drawbar and power take-off. Use of drawbar power is more convenient but less efficient and possible through either single or three-point hitch system. The hitching system significantly affects the tractor performance. There are several studies (Bentaher *et al*., 2008; Čupera & Šmerda, 2010; Čupera *et al*., 2011; Molari *et al*., 2014; Prasanna Kumar, 2015) on three-point hitch system to improve the tractor performance. Single hitch point (Fig. 1a) is largely used in transport/haulage activities, which are more than 50% of total tractor use in India (Kumar, 1994; Tiwari, 2017). The tractor performance in haulage is influenced mainly by the location of the hitch point, *i.e.* the horizontal distance from the center line of the rear axle and the vertical height from the ground (Fig. 1b). There have been few research studies on vertical height (Sahay & Tiwari, 2004; Šmerda & Bauer, 2007; Pranav *et al*., 2012, 2015; Kumar & Raheman, 2015) of single hitch point, but no attempt has been made for the hitch distance (HD) on haulage performance. Theoretically, the HD also affects the weight transfer (Eq. 1), especially in case of inclined pull which ultimately plays the role between traction and stability.

$$\text{Weight transfer} = \frac{\text{Hitch\_height} \times \text{Draft} + \text{Hitch\_distance} \times \text{Vertical\_force}}{\text{Wheelbase}} \quad (1)$$

Further, based on the data of 23 tractor's models as given in Table 1, it has been observed that there is no strong correlation between tractor power with hitch location. Again, no relation was found between HD and hitch height (Fig. 2). This clearly indicates that manufactures arbitrarily fix the hitch location as per the convenience of available space irrespective of tractor power, location of

a) b)

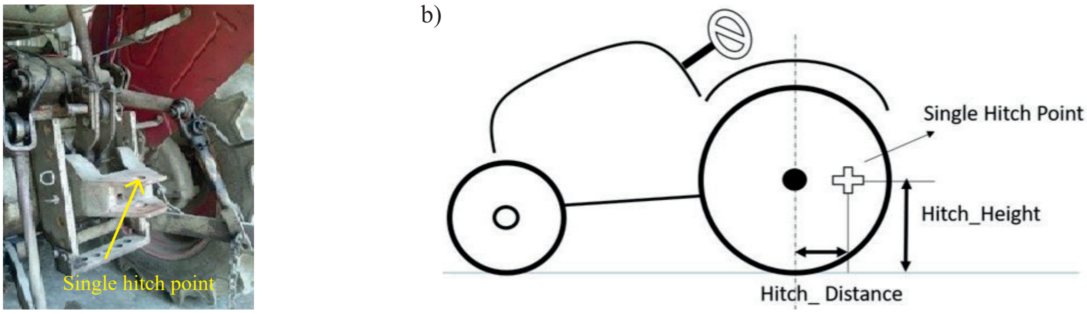

Figure 1. Tractor single hitch system: a) single hitch point, b) representation of a single hitch point

Table 1. Hitch location of rear wheel drive tractors.

Sl. No.	Tractor Make/ Model	PTO power, kW	Hitch distance from the rear axle, mm	Hitch height from the ground, mm		
				Max	Min	Average, mm
1	Eicher 5150	31.6	460	785	495	640
2	Escort 335 Josh Plus	20.8	310	725	725	725
3	Farmtrac 35 Champion	25.0	440	675	485	580
4	Farmtrac 45XT	27.9	435	700	515	608
5	Farmtrac50EPI	30.6	400	810	500	655
6	Farmtrac 60XT	31.3	440	695	505	600
7	Farmtrac 65 EPI	34.1	490	730	550	640
8	Farmtrac 60 DX	31.3	310	707	707	707
9	John Deere 5038 D	25.8	465	770	470	620
10	John Deere 5041 C	26.8	280	590	440	515
11	John Deere 5104	30.1	475	685	485	585
12	John Deere 5036	23.1	365	595	435	515
13	John Deere 5310	37.4	586	767	547	657
14	John Deere 5310 2T	38.1	545	795	575	685
15	M&M YUVO265 DI	23.2	490	655	375	515
16	M&M YUVO415	26.1	485	675	400	538
17	M&M B275DI	24.7	525	540	400	470
18	Powertrac 435	25.6	300	730	730	730
19	Powertrac 445XL	27.0	455	610	525	568
20	Powertrac 4455	33.7	415	700	515	608
21	Powertrac 4455DX	31.6	415	660	520	590
22	Powertrac 434	24.9	287	735	735	735
23	HMT2511	18.5	350	720	520	620
	Average		423	698	528	613

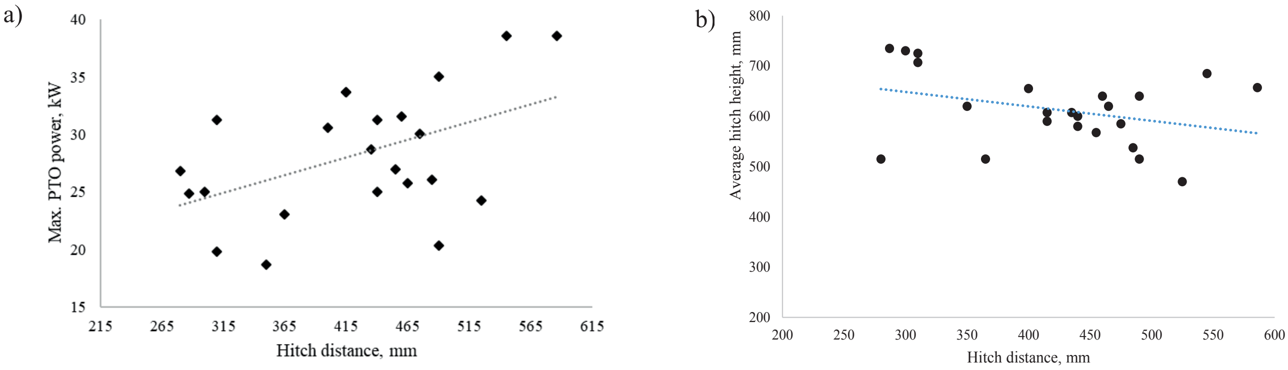

Figure 2. Relation of hitch distance in existing tractor models with a) maximum PTO power; b) hitch height

centre of gravity (CG), etc. The lack of studies in this aspect sacrifices either traction or stability. Therefore, this study was undertaken to theoretically analyze the effect of HD on tractor performance. It is well proven that theoretical analysis becomes fast, accurate and exhaustive by developing the computer program as performed by many researchers (Al-Hamed & Al-Janobi, 2001; Abu-Hamdeh & Al-Jalil, 2004; Pranav & Pandey, 2008; Kumar & Pandey, 2009; Kumar Prasanna, 2012; Dhruv *et al*., 2018). Keeping this aspect in mind the study was planned with the following specific objectives: (i) to develop a computer program for predicting haulage performance of 2WD tractors, and ii) to analyze the importance of HD on haulage performance.

Methodology

Theoretical considerations

The theoretical and empirical equations used in this study for developing the computer program are presented in this section.

— Pull force

$$\text{Draft} = ((\text{TrailerEmptyWt}+\text{PayloadWt})\times\text{Sin(Slope)}) + ((\text{TrailerEmptyWt}+\text{PayloadWt})\times(\text{Acceleration}/\text{GBL\_g})) + (\text{DynamicWt\_Trailer}\times\text{Rolling RegistanceCoeff\_Trailer}) \quad (2)$$

$$\text{Pull\_Y} = ((\text{TrailerEmptyWt}+\text{PayloadWt})\times\text{Cos(Slope)}) - \text{DynamicWt\_Trailer} \quad (3)$$

— *Rolling radius:*

$$\text{RollingRad} = \frac{2.5\times(\text{Dia}/2)\times\text{StaticLoadedRad}}{1.5\times(\text{Dia}/2)+\text{StaticLoadedRad}} \quad (4)$$

$$\text{Dia} = 1.06\times\text{RimDia}+2\times\text{Aspect}\times\text{SecWidth} \quad (5)$$

$$\text{StaticLoadedRad} = (\text{Dia}/2)\text{-Deflection}\times\text{Aspect}\times\text{SecWidth} \quad (6)$$

— *Aspect ratio.* It is defined as the ratio of section height to the section width of tyre:

$$\text{Aspect Ratio}=\frac{\text{SecHeight}}{\text{SecWidth}} \quad (7)$$

— *Coefficient of rolling resistance* (CRR) (Brixius, 1987)

$$\text{CRR\_Front}=(1/\text{BrixMobFront})+0.04 \quad (8)$$

$$\text{CRR\_Rear}=(c_5/\text{BrixMobRear})+c_4+(c_6\times\text{Slip}/\text{BrixMobRear\^{}0.5}) \quad (9)$$

$$\text{CRR\_Trailer}=(1/\text{BrixMobTrailer})+0.04 \quad (10)$$

$$\text{BrixMob}=\frac{\text{CI}\times\text{SecWidth}\times\text{Dia}}{\text{DynamicWeight}/2}\times\frac{1+5\times\frac{\text{Deflection}}{\text{SecHeight}}}{1+3\times\frac{\text{SecWidth}}{\text{Dia}}} \quad (11)$$

— *Eccentricity:*

$$\text{Eccentricity}=\text{RollingRad}\times\text{CRR} \quad (12)$$

— *Gross/Net traction ratio:*

$$\text{GTR}=\text{c1}\times(1\text{-Exp}(\text{-c2}\times\text{BrixMobRear}))\times(1\text{-Exp}(\text{-c3}\times\text{Slip}))+\text{c4} \quad (13)$$

$$\text{NTR\_Emperical}=\text{GrossTractionRatio-RollingResistanceCoeff\_Rear} \quad (14)$$

$$\text{NTR\_Theoretical}=\frac{\text{Draft}}{\text{DynamicWt\_Rear}} \quad (15)$$

— *Reaction at trailer wheel.* The dynamic weight of the trailer was calculated by taking moment about hitch point from the trailer's free body diagram as shown in Fig. 3a.

$$\text{DynamicWt\_Trailer} = \frac{[(\text{PayloadWt}+\text{TrailerEmptyWt})\times\cos(\text{Slope})\times\{(\text{TrailerWheelAxis\_DistanceFromHitchPt} - \text{TrailerCG\_X}) + (\text{Acceleration}/\text{g}+\sin(\text{Slope})\times(\text{TrailerCGwithMaterial\_Y} - \text{HitchHeight\_1})\}]}{[\text{RollingResistanceCoeff\_Trailer}\times(\text{HitchHeight\_1} - \text{RollingRadius\_Trailer}) + \text{TrailerWheelAxis\_DistanceFromHitchPt}]} \quad (16)$$

a)

b)

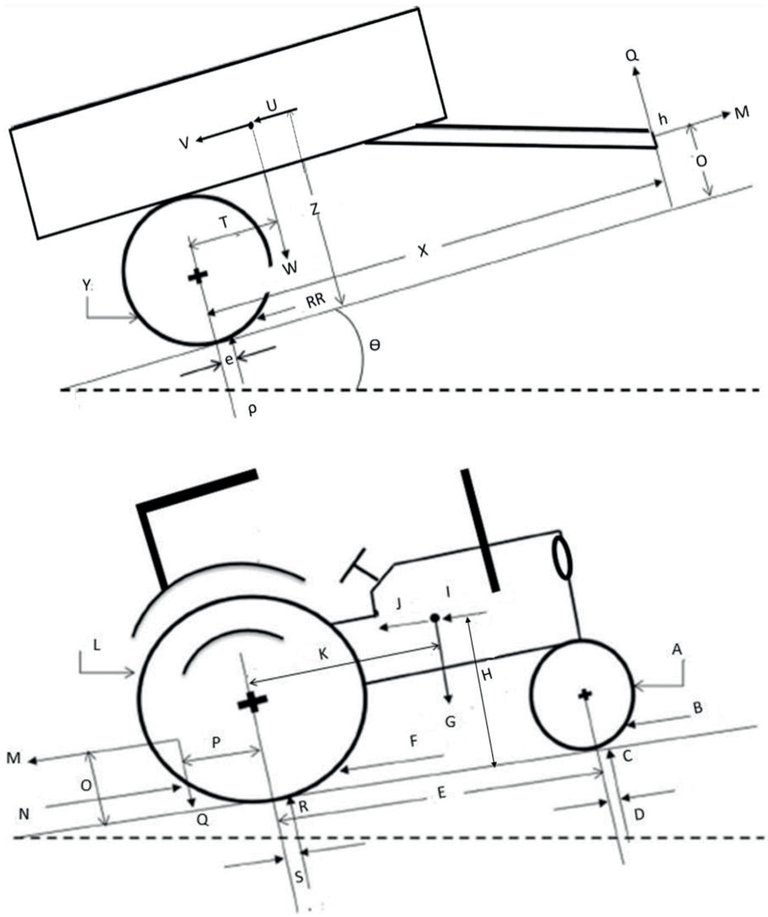

Figure 3. Free body diagram in dynamic condition of: (a) unbalanced trailer (h, hitch point; O, hitch height; e, eccentricity_trailer; T, tractor CG_X; U (payload Wt + trailer empty Wt) × (acceleration⁄GBL_g); V (payload Wt + trailer empty Wt) × sin (slope); W (payload Wt + trailer empty Wt) × cos (slope); X, trailer wheel axis dist from hitch Pt; Y, Dia Trailer; Z, Trailer CG with material_Y; RR, rolling resistance at trailer; Θ, road slope; ρ, dynamic Wt_Trailer); (b) rear wheel drive tractor (A, DiaFront; B, rolling resistance at front; C, dynamic Wt_Front; D, Eccentricity_Front; E, wheel base; F, rolling resistance at rear; G, total Wt × cos (slope); H, tractor CG_Y; I, total Wt × (Acceleration⁄GBL_g); J, total Wt × sin (slope); K, tractor CG_X; L, DiaRear; M, draft; N, pull; O, hitch height; P, hitch distance; Q, pull_Y; R, dynamic Wt_Rear; S, eccentricity_rear).

$$\text{TotalWt} = \text{StaticWeight\_Front} + \text{StaticWeight\_Rear} \quad (17)$$

$$\text{TractorCG\_X} = \frac{\text{StaticWeight\_Front} \times \text{WheelBase}}{\text{TotalWt}} \quad (18)$$

$$\text{TractorCGwithMaterial\_Y} = \text{TrailerCGEmpty\_Y} + \frac{\text{PayloadWt} \times \text{PayloadHt}/2}{\text{PayloadWt} + \text{TrailerEmptyWt}} \quad (19)$$

— *Reaction at front/rear wheel.* The dynamic weight of the trailer was calculated by taking moment about hitch point from the tractor's free body diagram in dynamic condition as shown in Fig. 3b

$$\text{DynamicWt\_Rear} = \frac{\begin{array}{l}[\{\text{TotalWt} \times (\text{WheelBase} - \text{TractorCG\_X} + \text{Eccentricity\_Front}) \times \\ \cos(\text{Slope})\} + \{\text{TotalWt} \times \text{TractorCG\_Y} \times (\text{Acceleration}/\text{GBL\_g} + \\ \sin(\text{Slope})\} + \{\text{Pull\_Y} \times (\text{HitchDistance\_1} + \text{WheelBase} + \\ \text{Eccentricity\_Front})\} + \text{Draft} \times \text{HitchHeight\_1}]\end{array}}{\text{WheelBase} + \text{Eccentricity\_Front} - \text{Eccentricity\_Rear}} \quad (20)$$

— *Front wheel utilisation factor.* Front wheel utilization factor is the ratio of dynamic weight on the axle to the total weight of the tractor.

$$\text{FrontWheelUtilizationFactor} = \frac{\text{DynamicWt\_Front}}{\text{TotalWt}} \quad (21)$$

— *Actual engine power required.* The actual engine power used is defined as the ratio of axle power to transmission efficiency.

$$\text{EquivalentBrakePwr} = \frac{\text{Draft} \times \text{ActualSpeed}}{\text{TractiveEfficinecy} \times \text{TransmissionEfficiency}} \quad (22)$$

— *Transport productivity.* Transport productivity is the product of payload transported and the forward velocity.

$$\text{TransportProductivity} = \text{PayloadWt} \times \text{ActualSpeed} \quad (23)$$

$$\text{ActualSpeed} = \text{TheoriticalSpeed} \times (1 - \text{Slip}) \quad (24)$$

— *Transport efficiency.* Transport efficiency is the ratio of transport productivity to the input power.

$$\text{Transport\_Efficiency} = \frac{\text{TransportProductivity}}{\text{EquivalentBrakePwr}} \quad (25)$$

— *Fuel economy index.* Fuel economy index is the amount of fuel consumed per unit payload over a unit distance.

$$\text{FuelEconomyIndex} = \frac{\text{SpecificFuelConsumption} \times \text{EquivalentBrakePwr}}{\text{TransportProductivity}} \quad (26)$$

— *Gradient resistance*

$$\text{GradeResistance} = \text{TotalWt} \times \sin(\text{Slope}) \quad (27)$$

— *Power utilisation factor*

$$\text{PwrUtilizationFactor} = \frac{\left(\text{DrawbarPwr} + \left(\begin{array}{c}\text{RollingResistanceCoeff\_Front} \times \\ \text{DynamicWt\_Front} \times \text{ActualSpeed}\end{array}\right)\right)}{(\text{TractiveEfficiency} \times \text{TransmissionEfficiency})} \times \frac{1}{\text{BrakePwr}} \quad (28)$$

Development of the computer program

A program was written in Visual Basic 10 environment for evaluating the haulage performance of rear wheel drive tractor with an unbalanced trailer at different operating conditions by varying the HD. The flow chart of the developed program is shown in Fig. 4, where the sequence of calculations and equations used are indicated. The program gives a warning sign if either stability or engine power fails. A warning sign for stability performs when the front utilization factor is lower than 0.2 as per the minimum load requirement for longitudinal stability (Horton & Crolla, 1984).The input and output windows of the developed program are shown in Fig. 5.

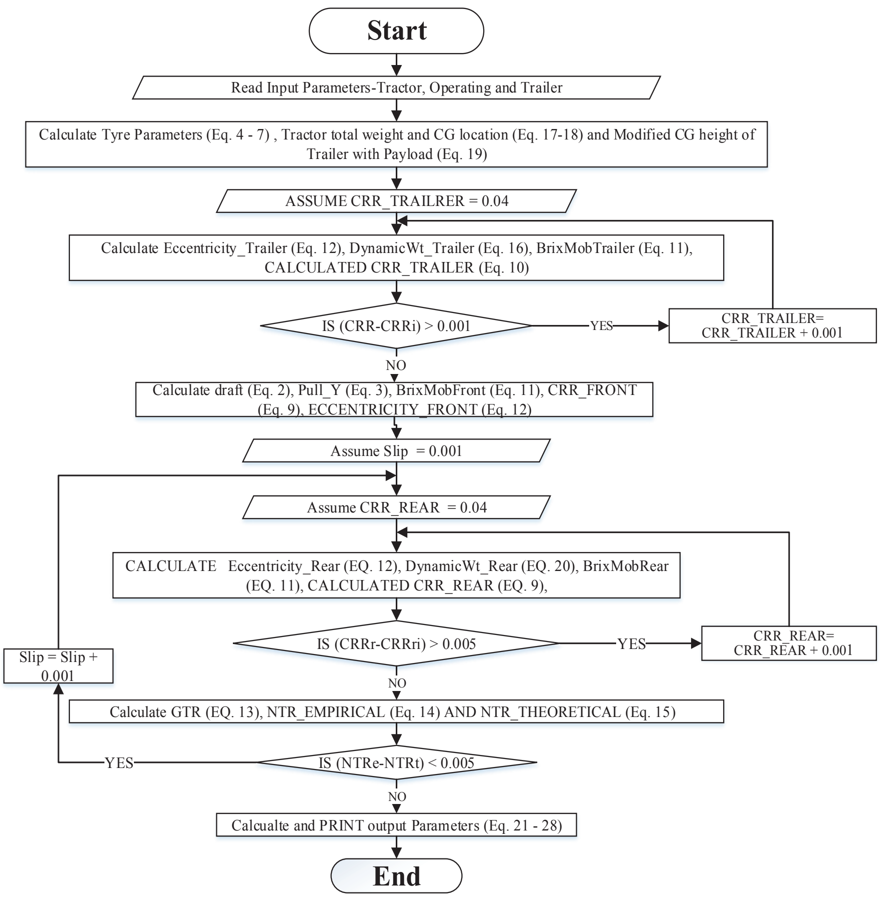

Figure 4. Flow chart of the developed program

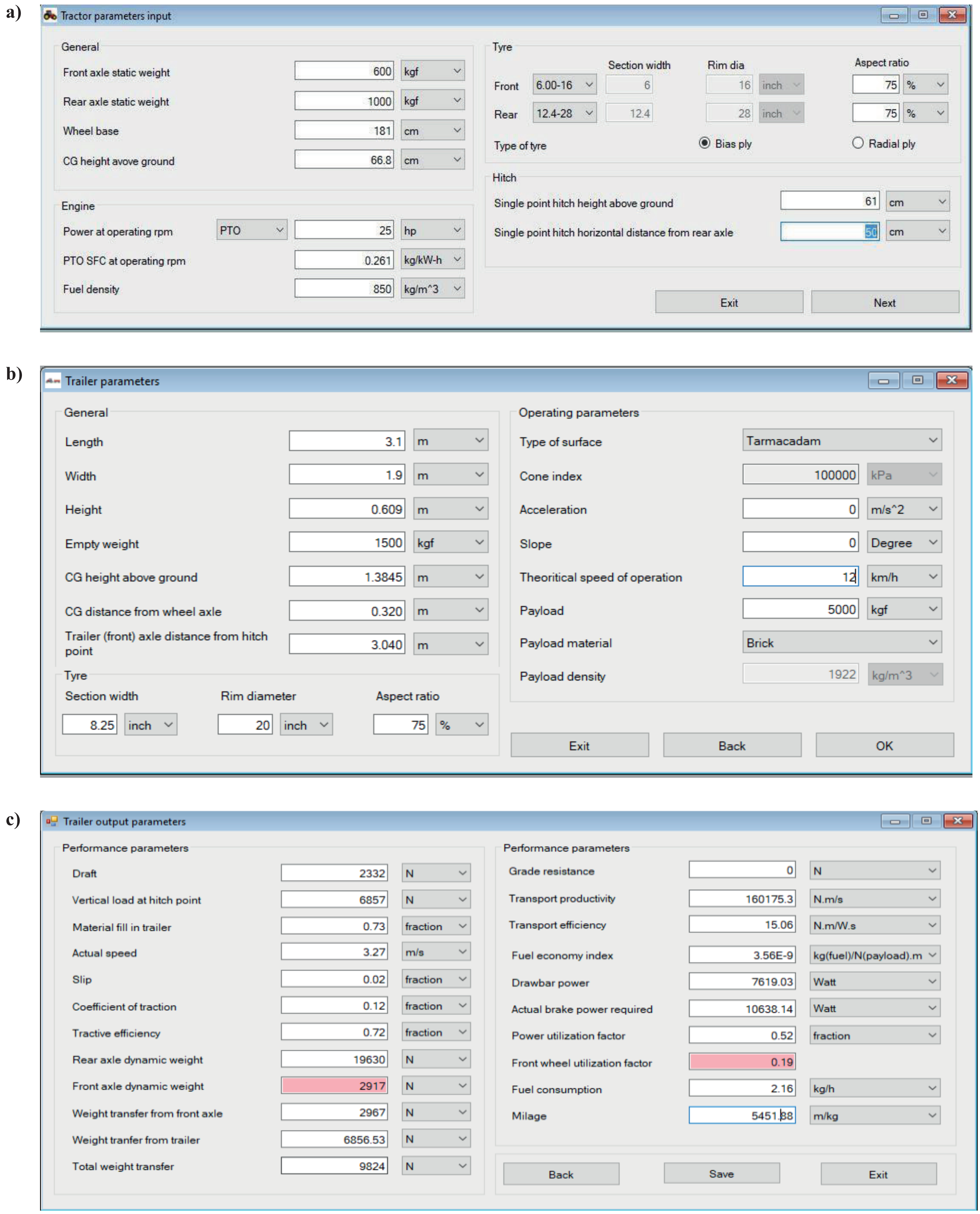

Figure 5. Windows of the developed program for parameters: a) tractor input; b) trailer input; c) output

Results and discussion

Prediction of haulage performance

The developed program was used to estimate the haulage performance of a tractor with an unbalanced trailer for different operating conditions. Input parameters to run the program are given in Table 2 and output parameters are listed in Table 3. The predicted haulage performance is very close to the performance predicted by Kumar & Pandey (2009) and Pranav *et al.* (2015). Therefore, the developed program was used to examine the effect of HD on tractor performance and their stability.

Benefits of smaller hitch distance

Effect of HD on maximum payload, transport productivity, and maximum slope is shown in Fig. 6. The Fig. 6a reveals that there was a significant increase in payload of 5700 kg at 0^0 slope when HD was reduced from 0.8 to 0.2 m, whereas the change in payload at slopes 5 and 10^0 was marginal of 1340 and 370 kg, respectively. This clearly indicates that lower HD is advantageous at lower slope, because the slope has a more prominent effect on maximum payload compared to HD.

The effect of HD on transport productivity was similar to maximum payload because transport productivity is the product of payload and speed of operation. It was observed that transport productivity increased to 66.05, 14.89 and 4.2 ton.km/h at 0, 5 and 10^0 slopes, respectively (Fig. 6b).

Further, Fig. 6c indicates that there was an advantage in achieving the maximum slope by reducing the HD at all payloads. It was observed that the increase in maximum slope was 55, 106, 205, and 445% by reducing the HD from 0.8 to 0.2 m for the payloads of 1000, 1500, 2000 and 2500 kg, respectively. This is because of the moment caused by the vertical force on the hitch point, which is directly proportional to HD. This moment is the source of weight transfer which results in limited slope.

Benefits of bigger hitch distance

The effect of HD on rear and front axle dynamic weight is shown in Fig. 7a. It is observed that rear axle dynamic weight increases with the increase in HD because of higher weight transfer due to the vertical component of pull force at hitch point. It was predicted that the increase in rear axle dynamic load was 6.67, 7.55 and 8.49% when HD increased from 0.2 to 0.8 m at 1000, 1500 and 2000 kg payloads, respectively. The increase in rear axle dynamic weight is due to the reduction in front axle dynamic weight, which was about 21, 27 and 34% for the same level of change in HD at 1000, 1500 and 2000 kg payloads.

Actual engine power and fuel economy index increased with increase in HD up to 0.7 m. After 0.7 m of HD, both parameters started reducing. This clearly indicates that the

Table 2. Input parameters used for program run.

Tractor		Trailer		Operating conditions	
Front wheel static weight, kgf	600	Length, m	3.1	Type of surface	Tarmacadam
Rear wheel static weight, kgf	1000	Width, m	1.9	Cone index, kPA	10000
Wheel base, cm	181	Height, m	0.609	Acceleration, m/s^2	0
Cg height above ground, m	66.8	Empty weight, kgf	1500	Slope, ^{o}	0 and 4
Engine power, hp	25	CG height above	1.385	Theoretical speed of operation, km/h	12 and 17
SFC at operating rpm,	0.261	ground, m			
kg/kwh-h	0.735				
Tyre size (front wheel), m	0.735	CG distance from	0.320	Payload, kgf	1000,1500&2000
Tyre size (rear wheel), m	1.27	wheel axle, m		Payload material	Brick
Type of tyre	Bias	Trailer axle hitch	3.040	Density of material,	1922
	Ply	distance point, m		kg/m^3	
Hitch height above ground, cm	61				
Hitch distance from the rear	50	Tyre size, m	0.895		
axle, cm					

Table 3. Output parameters of the program based used input parameters.

Input parameters						Output parameters								
Ө	**Vt**	**D**	**VL**	**Va**	**S**	**NTR**	**TE**	**R**	**Puf**	**FWUf**	**FEI**	**GR**	**TrE**	**TrP**
PL=1000 kg														
0	12	88	263.6	3.3	0.01	0.06	0.58	1368	0.32	0.30	0.1088	0.00	2.09	11.7
	17	88	263.6	4.7	0.01	0.06	0.58	1368	0.46	0.30	0.1088	0.00	2.09	16.6
4	12	260	218.5	3.2	0.03	0.18	0.79	1406	0.60	0.24	0.2372	1094	0.96	11.5
	17	260	218.5	4.6	0.03	0.18	0.79	1406	0.85	0.24	0.2372	1094	0.96	16.3
PL=1500 kg														
0	12	105	316.3	3.3	0.01	0.07	0.62	1442	0.35	0.28	0.0807	0.00	2.81	17.6
	17	105	316.3	4.7	0.01	0.07	0.62	1442	0.49	0.28	0.0807	0.00	2.81	24.9
4	12	312	261.1	3.2	0.04	0.21	0.80	1479	0.69	0.22	0.1859	1094	1.22	17.1
	17	312	261.1	4.6	0.04	0.21	0.80	1479	0.98	0.22	0.1859	1094	1.22	24.3
PL=2000 kg														
0	12	126	369.2	3.3	0.01	0.08	0.64	1517	0.39	0.27	0.0704	0.00	3.22	23.4
	17	126	369.2	4.7	0.01	0.08	0.64	1517	0.55	0.27	0.0704	0.00	3.22	33.2
4	12	367	303.5	3.2	0.04	0.24	0.80	1553	0.80	0.20	0.1643	1094	1.38	22.7
	17	367	303.5	4.5	0.04	0.24	0.80	1553	1.14	0.20	0.1643	1094	1.38	32.2

PL – payload; Ө – slope, degree; Vt - theoretical velocity, km/h; D – draft, kg; VL - pull_Y, kg; Va – actual velocity, km/h; S – slip, % NTR - net traction ratio; TE - tractive efficiency, %; R, dynamic Wt_Rear, kg; Puf - Pwr utilisation factor; FWUf - front wheel utilisation factor; FEI - fuel economy index; GR – gradient resistance, kg; TrE - transport efficiency, ton-km/kW; TrP - transport productivity, L/ton-km

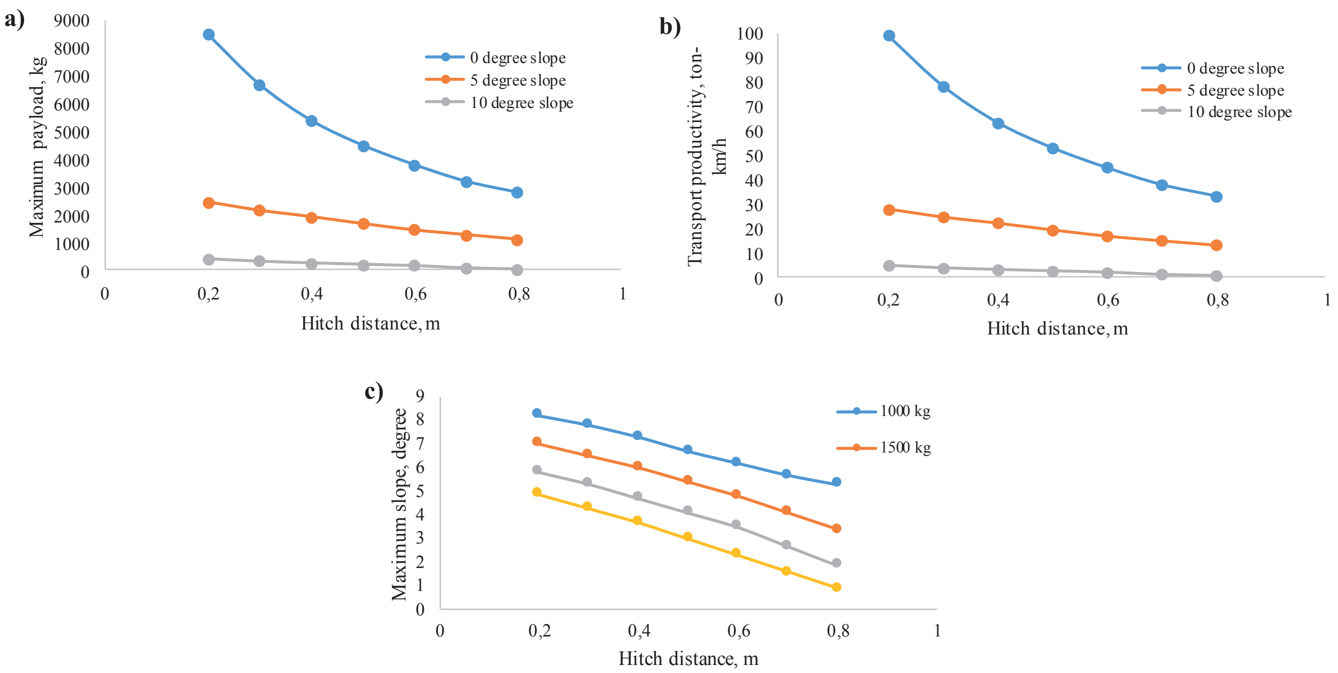

Figure 6. Effect of hitch distance at hitch height of 0.61 m on: a) maximum payload; b) transport productivity; c) maximum road slope

a)

b)

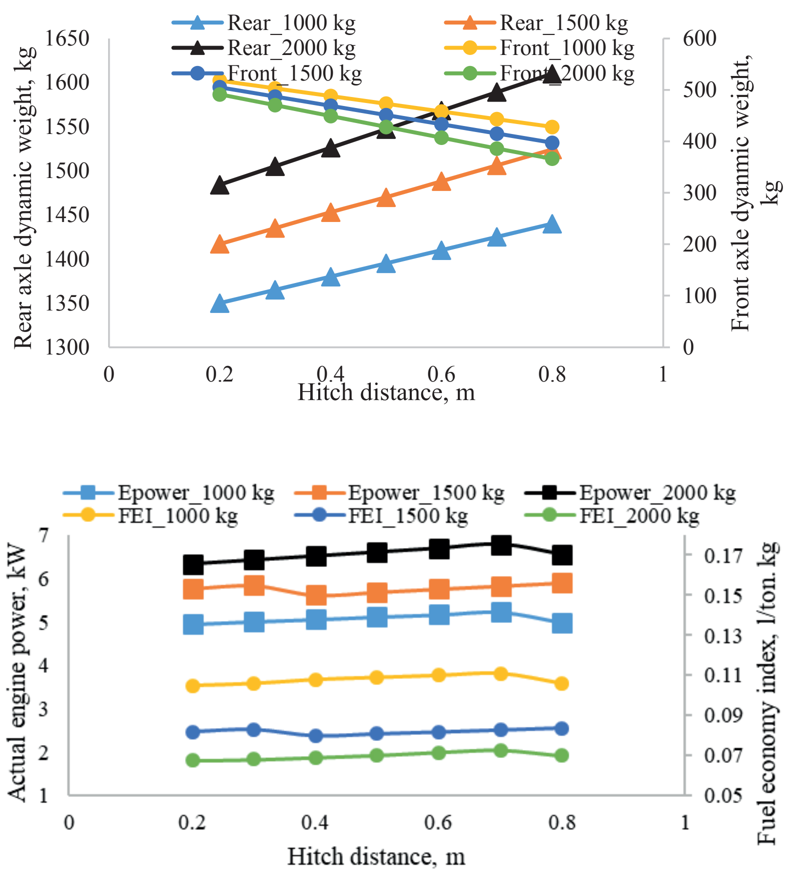

Figure 7. Effect of hitch distance at hitch height $^{0.61}$ m on: a) dynamic load; b) engine power and FEI (fuel economy index)

HD beyond 0.7 m improves the traction and as a result, saves the fuel consumption. This is because of the higher dynamic load, which creates higher rolling resistance at bigger HD compared to lower HD as shown in Fig. 7b.

It is well understood from the above results that lower HD is beneficial in increasing the maximum payload, transport productivity as well as maximum slope. At the same time, it reduces the rear wheel dynamic load, the fuel economy index and the actual engine power requirement. This clearly indicates that when maximum payload or slope is limited by longitudinal stability and having sufficient engine power as well as traction, the reduced HD is advantageous. Further, if longitudinal stability is intact and traction or engine power is limited, higher HD will be beneficial. In one go of haulage operation, all the three limitations, traction, longitudinal stability and power arises due to variation in road slope and conditions. Therefore, a variable HD in the tractor will help in increasing the work output as well as the efficiency of the existing tractor.

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