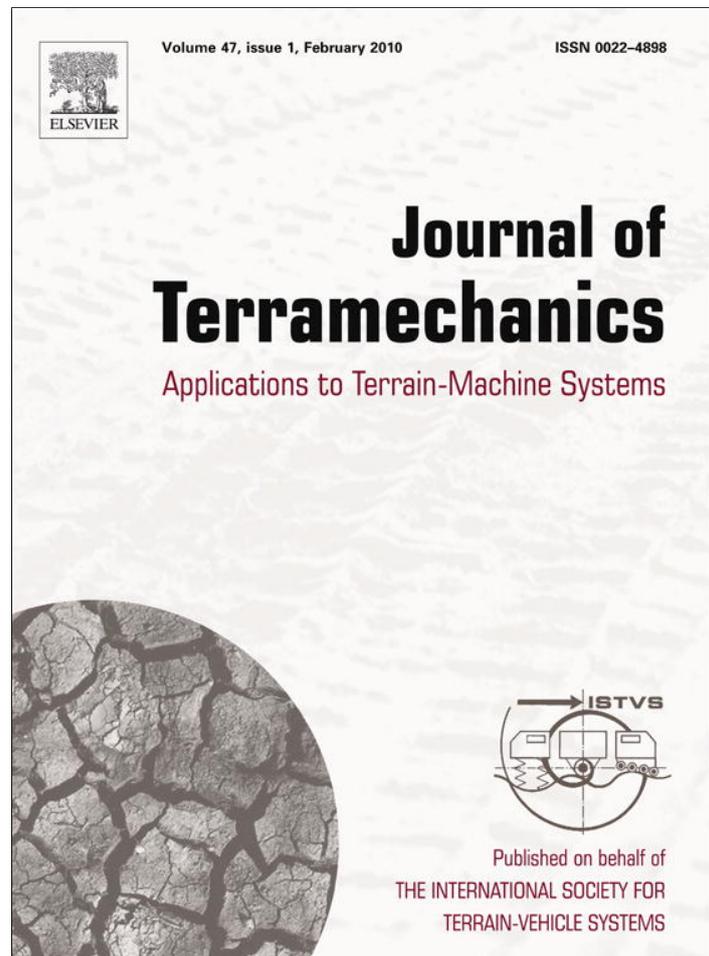


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## Development of hybrid electrical air-cushion tracked vehicle for swamp peat

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### Abstract

This study presents a developed hybrid electrical air-cushion tracked vehicle (HETAV) for the transportation operation of agricultural and industrial goods on the swamp peat terrain bearing capacity of 5 kN/m<sup>2</sup>. The vehicle's design parameters are optimized by using the developed mathematical models which are made based on the kinematics and dynamics behaviors of the vehicle. A set of sensors are used with this vehicle to activate the air-cushion system and battery pack recharging system. The vehicle's air-cushion system is protected by a novel-design auto-adjusting supporting system. The air-cushion dragging motion resistance is overcome with additional thrust which is developed by a propeller. The vehicle is equipped with the air-cushion system to make the vehicle ground contact pressure 5 kN/m<sup>2</sup>.

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### 1. Introduction

This is a custom-built light weight small-scale vehicle is made for the transportation operation of agricultural and industrial goods on swamp peat in Malaysia. The propulsion system of the vehicle is comprised of tracks and air-cushion system as shown in Fig. 1. The track mechanism is used as the driving system to overcome the rolling motion resistance and the air-cushion system is used to increase the floatation capacity of the vehicle. The driving force is provided to each of the tracks by an individual DC motor. The air-cushion system of this vehicle was designed in such a way that it would not slide on the terrain with the vehicle movement. It only supports the partial load of the vehicle once the vehicle sinkage is closed to 50 mm and makes the vehicle ground contact pressure 5 kN/m<sup>2</sup> [12]. The additional thrust (or tractive effort) is provided to the vehicle by using a propeller to overcome the drag motion resistance of the air-cushion system. As

the terrain is unprepared and different types of decomposed materials are on the terrain, the air-cushion system was protected by using a Novel designed supporting system. It adjusts the air-cushion system on the terrain automatically by absorbing its longitudinal displacement with two horizontally attached shock absorbers and vertical displacement with four vertically attached springs.

Different types of vehicles are introduced to solve the transportation problems on moderate peat terrain [1–5]. But still no one offers any vehicle on low bearing capacity swamp peat terrain in Malaysia. The proposed vehicle could be useful for transporting the palm oil fresh fruit bunches over the swamp peat.

### 2. Material and methods

The mathematical model is formulated by understanding the terrain nature, analyzing the mechanics of track-terrain interaction, and simplifying the recommended mathematical models of Ataur et al. [17], Wong [18]. The solutions to this set of equations define the vehicle sinkage,

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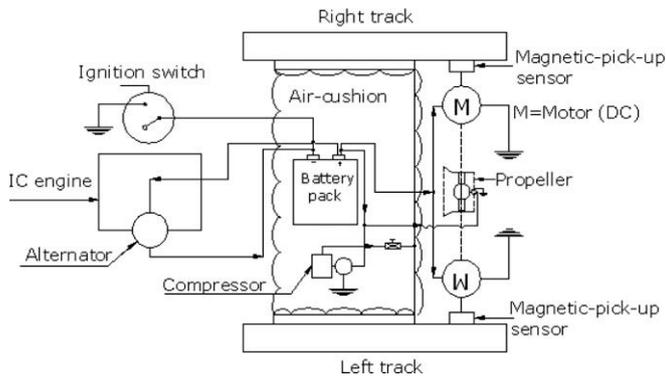


Fig. 1. Vehicle power transmission system.

slippage, entry and exit angle of the track. Based on the set of equations, the vehicle ground pressure distribution, dynamic load distribution, motion resistance, and tractive effort are simulated. The tractive effort and motion resistance of the vehicle are formulated in this study based on two sinkage conditions: (i) sinkage,  $0 \leq z \leq 70$  mm and (ii) sinkage,  $z \geq 70$  mm. Assumptions are made in order to establish the mathematical models: (i) the pressure distribution in the track–terrain interface is assumed to be uniform by locating the vehicle C.G at the mid point of the track system and (ii) critical sinkage of the vehicle is considered to be 70 mm based on the study of Jamaluddin [12].

Consider a track vehicle of total weight  $W$ , track size including track ground contact length  $L$ , width  $B$ , pitch  $T_p$ , and grouser height  $H$ , radius of the rear sprocket  $R_{rs}$ , and radius of the road-wheels  $R_r$ , and height of the center of gravity  $h_{cg}$  is traversing under traction on a swamp peat terrain at a constant speed of  $v_t$  as soon as applying the driving torque  $Q$  at the rear sprocket. The pressure distribution in the track–terrain interface is assumed to be uniform by locating the vehicle C.G at the mid point of the track system. The pressure at main straight part  $P$ , and rear sprocket  $P_{rs}$ , and the sinkage of the vehicle  $z$  is as shown in Fig. 2.

The traction (tractive effort) equation for the bottom of the vehicle's track ground contact part on peat terrain is computed by simplifying the recommended equation of Ref. [16]:

(i) For sinkage,  $0 \leq z \leq 70$  mm

$$F_b = (A_t c + (W_t) \tan \phi) \left[ \frac{K_w}{iL} e^1 - \left( 1 + \frac{K_w}{iL} \right) \exp \left( 1 - \frac{iL}{K_w} \right) \right] \quad (1)$$

where,  $A_t = 2(L_{YZ})(B)$  and  $L = L_{YZ}$ .

In Eq. (1),  $F_b$  is the traction that develops at the bottom part of the track in kN,  $L$  is the ground contact length of the track in m,  $A_t$  is the area of the track ground contact area in  $m^2$ ,  $W_t$  is the vehicle load supported by the track system in kN,  $c$  is the cohesiveness in  $kN/m^2$ ,  $\phi$  is the terrain internal friction angle in degrees,  $K_w$  is the shear deformation modulus of the terrain in m,  $i$  is the slippage of the vehicle in percentage, and  $B$  is the width of the track in m.

(ii) For sinkage,  $z \geq 70$  mm

When the vehicle sinkage is 70 mm or more, the cushion-system of the vehicle will be in contact with the terrain. Therefore, the additional thrust of the vehicle will be needed to develop in order to overcome the dragging motion resistance of the vehicle. The traction of the vehicle  $F_t$  is calculated by using the recommended equation of Wong et al. [6] and Bodin [10]:

$$F_t = (A_t c + W_t \tan \phi) \times \left[ \frac{K_w}{iL} e^1 - \left( 1 + \frac{K_w}{iL} \right) \exp \left( 1 - \frac{iL}{K_w} \right) \right] + R_{drag} \quad (2)$$

where,  $A_t = (L_{XY} \cos \theta + L_{YZ} + R_{rs} \sin \theta)(2B)$ ,  $L = (L_{XY} \cos \theta + L_{YZ} + R_{rs} \sin \theta)$  and  $L_{XY} = \frac{z}{\sin \theta}$ .

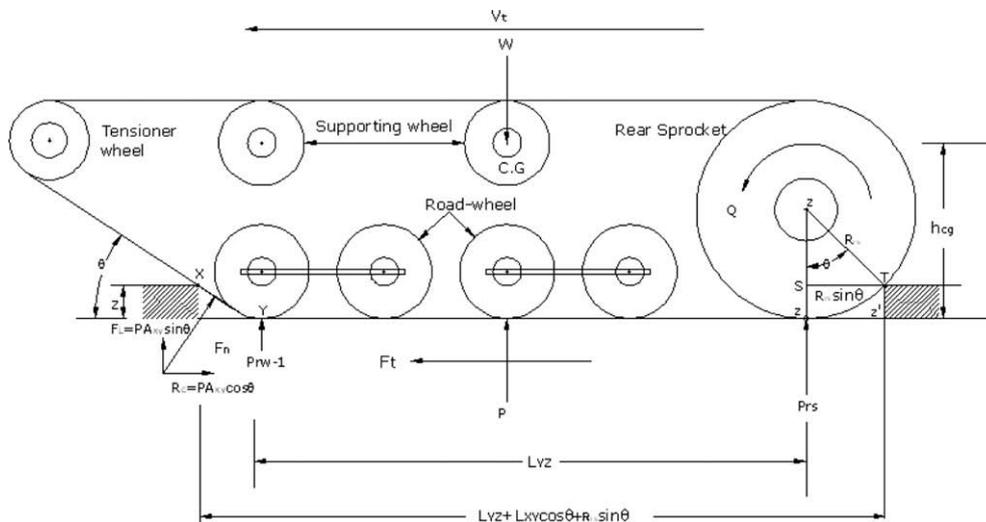


Fig. 2. Force acting on track system.

In Eq. (2),  $R_{drag}$  is the drag motion resistance which is developed due to the sliding of the air-cushion system over the terrain in kN and  $\theta$  is the angle between the track of the 1st road-wheel to tensioned wheel and to the ground in degrees.

Fig. 3 shows the novel-design-air-cushion protecting system. It is made of aluminum alloy. This system is to protect the air-cushion system from the external threat on the ground by adjusting its vertical and longitudinal displacements automatically. The air-cushion system is attached with the HETAV only for stopping the vehicle sinkage and increase the vehicle floatation capacity. It would be incurred for the vehicle once the vehicle transfers its load to the air-cushion system. Load transferring of the vehicle to the air-cushion system starts when the vehicle sinkage is 70 mm or more. The load transfer of the vehicle to the air-cushion system  $W_{v(ac)}$  could be formulated as follows:

$$W_{v(ac)} = (P' - P)(A_{BC}) \quad (3)$$

where,  $P = \left(k_p z + \frac{4}{D_m} m_m z^2\right)$  and  $P' = \frac{W}{2A_i}$

(i) For vehicle sinkage,  $z = 0.0$  mm

$$W_{v(ac)} = 0 \quad (4)$$

(ii) For vehicle sinkage,  $z > 70$  mm

$$W_{v(ac)} = \left[ P' - \left( k_p z_{acs} + \frac{4}{D_{hac}} m_m z_{acs}^2 \right) \right] (A_{BC} + 2A_{BC'}) \quad (5)$$

where

$$z_{acs} = \frac{-\left(\frac{k_p D_{acs}}{4m_m}\right) \pm \sqrt{\left[\left(\frac{k_p D_{acs}}{4m_m}\right)^2 + \frac{D_{acs} P'_0}{m_m}\right]}}{2} \quad \text{and}$$

$$D_{acs} = \frac{4(B_{acs})(L_{BC} + 2L_{BC} \cos \theta)}{(L_{BC} + 2L_{BC} \cos \theta + B_{acs})}$$

In Eq. (3),  $P$  is the ground nominal pressure (GNP) in  $\text{kN/m}^2$ ,  $P'$  is the vehicle ground contact pressure (VGP) in  $\text{kN/m}^2$ , and  $A_{BC}$  is the contact area of the air-cushion

support system as shown in Fig. 3. It is noted that when the vehicle sinkage is zero or less than 70 mm (i.e.,  $0.0 \text{ mm} \leq z < 70 \text{ mm}$ ), the air-cushion will be not in contact with the terrain. In swamp peat terrain it is absolutely not possible to make any vehicle including this vehicle sinkage zero (i.e.,  $z = 0$ ). While in some instances it could be less than 70 mm. The sinkage of this vehicle will be more than 70 mm if the vehicle is not equipped with an air-cushion system. Therefore, the vehicle sinkage will be limited to 70 mm by using an air-cushion system. The air-cushion system supports the vehicle's partial load and also makes the vehicle ground contact pressure less than the ground nominal pressure.

In Eqs. (4) and (5),  $z_{acs}$  sinkage of the air-cushion-support system in m,  $D_{acs}$  is the hydraulic diameter with respect to the air-cushion-support system in m. The contact area of the air-cushion,

(i) For sinkage,  $z = 70$  mm

$$A_{BC} = BL_{BC} \quad (6)$$

(ii) For sinkage,  $z > 70$  mm

$$A_{BCC'C'} = B(L_{BC} + 2L_{BC'} \cos \theta) \quad (7)$$

As the air in the air-cushion is compressible, the sinkage of the air-cushion support system increases with increases in the vehicle sinkage. However, the sinkage of the air-cushion support will be limited to the point of  $C'C'$ . Theoretically, the contact length  $L_{BC'} = L_{CC'}$  is assumed to be constant. However, in practice it is not possible to maintain as the terrain is unprepared and comprised of decomposed materials. The instantaneous contact area of the air-cushion can be computed as,

$$A_{BC}(t) = BL_{BC} + 2B \cos \theta \int_0^{L_{CC'}} dl \quad (8)$$

The additional tractive effort which is developed by the propeller must be equal to the drag motion resistance of the air-cushion support system during sliding. The drag

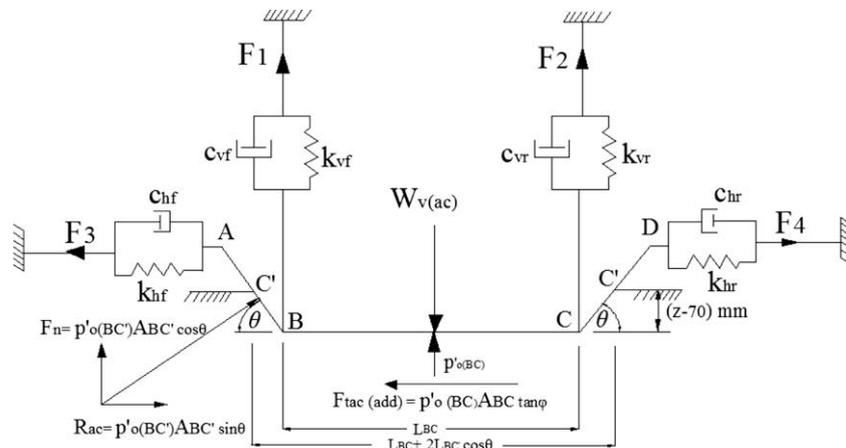


Fig. 3. Novel-designed air-cushion support system.

motion resistance of the air-cushion system is overcome by developing the additional thrust of the propeller. Therefore, the additional thrust,  $F_{tac(add)} = p'_o(BC)A_{BC} \tan \varphi = R_{drag}$  is shown in Fig. 3. The drag motion resistance  $R_{drag}$  of the air-cushion system based on the (Fig. 3), could be computed as follows:

(i) For sinkage,  $z = 0.0$  mm

$$R_{drag} = 0 \quad (9)$$

(ii) For sinkage,  $z = 70$  mm

$$R_{drag} = P'_o A_{BC} \tan \varphi = (P' - P)A_{BC} \tan \varphi \quad (10)$$

where  $P'_o$  is the pressure exit on the air-cushion system due to the vehicle's dynamic load transfer to the air-cushion system in  $\text{kN/m}^2$ .

(iii) For vehicle sinkage,  $z > 70$  mm

$$R_{drag} = P'_o(A_{BC'} + A_{CC'}) \sin \theta + P'_o A_{BC}(\tan \varphi) \quad (11)$$

For the sinkage,  $z > 70$  mm, the hydraulic diameter  $D_h$  of the vehicle for the track system will follow the same equation as stated in Eq. (5).

The motion resistance due to the terrain compaction can be calculated by considering (Fig. 2), as follows:

(iv) For sinkage,  $z = 0.0$  mm

$$R_c = 2PBL_{YZ} \tan \varphi \quad (12)$$

where

$$P = \left( k_p z + \frac{4}{D_{ht}} m_m z^2 \right), \quad z = \frac{-\left( \frac{k_p D_{ht}}{4m_m} \right) \pm \sqrt{\left[ \left( \frac{k_p D_{ht}}{4m_m} \right)^2 + \frac{D_{ht}}{m_m} P' \right]}}{2},$$

$$D_{ht} = \frac{4BL_{YZ}}{2(L_{YZ} + B)} \quad \text{and} \quad P' = \frac{W}{(L_{YZ})(2B)}$$

(v) For sinkage,  $z = 50$  mm

$$R_c = 2PBL_{YZ} \tan \varphi + 2PBL_{XY} \cos \theta \quad (13)$$

The total motion resistance of the vehicle could be incurred on the vehicle in two conditions: (i) if the vehicle sinkage is less than 70 mm, it would be mainly for compaction, and (ii) if the vehicle sinkage is equal to 70 mm or more, it will be due to both compaction and dragging.

It is noted that the air-cushion only supports the vehicle's partial load once the support system touches the terrain. So, the inflated pressure of the air-cushion makes the deflection of the spring until the support system touches the ground. Therefore, the pressure of the air-cushion can be defined by the summation of the spring forces which are vertically attached to the air-cushion support system as shown in Fig. 3 and dividing the contact area of the air-cushion support system. So, the pressure of the air-cushion is formulated as

$$P_{ac} = \frac{(4F_s)}{A_{sac}} = \frac{(4k_s \delta_s)}{A_{sac}} \quad (14)$$

where  $\delta_s = \int_{70}^z dz$ . In Eq. (14),  $\delta_s$  is the instantaneous deflection of the spring in mm,  $k_s$  is the spring constant in N/m,  $P_{ac}$  is the air-cushion pressure in  $\text{kN/m}^2$ , and  $A_{sac}$  the contact area of the air-cushion support system in  $\text{m}^2$ .

The additional thrust that is needed for the vehicle to overcome the dragging motion resistance of the air-cushion system is developed by using a propeller as shown in Fig. 4.

The vector diagram as shown in Fig. 4, is used to analyze the propeller geometry and its relationship to the flow of air. The subscripts  $i$  and  $o$  are used for the inlet and outlet flow conditions respectively,  $v$  ( $v = r\omega$ ) represents the peripheral velocity of the impeller,  $V_{alb}$  represents the air velocity relative to the propeller blade, and  $u$  is the absolute air velocity,  $\alpha$  is the angle between absolute and peripheral velocity in m/s, and  $\beta$  is the blade angle.

The torque applied to a propeller impeller must be equal to the difference of the momentum at the inlet to and outlet

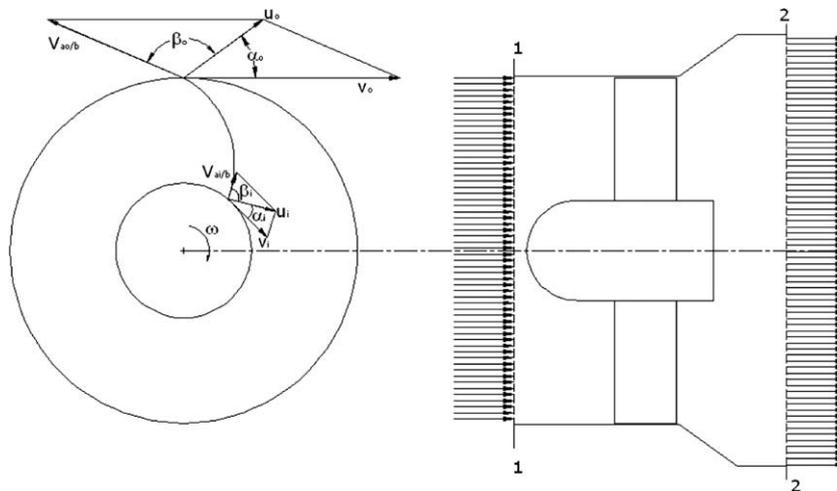


Fig. 4. Propeller for the vehicle.

from the impeller. It may be expressed as follows by using the equation:

$$T = \rho \int_Q r_o u_o \cos \alpha_o dQ - \rho \int_Q r_i u_i \cos \alpha_i dQ \quad (15)$$

For steady flow and uniform conditions around the impeller,  $r_o u_o \cos \alpha_o dQ$  and  $r_i u_i \cos \alpha_i dQ$  have constant values. Eq. (15) may be simplified to

$$T = \rho Q (r_o u_o \cos \alpha_o - r_i u_i \cos \alpha_i) \quad (16)$$

It is to be noted that the input power is equal to the output power of the DC propeller motor shaft. The input power  $P_i$  to the propeller can be computed as

$$P_i = T\omega = \rho Q \omega (r_o u_o \cos \alpha_o - r_i u_i \cos \alpha_i) \quad (17)$$

where  $P_i$  is the input power of the propeller motor in kW and  $\omega$  is the angular velocity of the impeller in rad/s. The propeller motor is powered by the battery pack.

The output power of a propeller is expressed in terms of the propeller discharge and the total energy head  $H_p$  that the propeller imparts to the air. The energy is added to the fluid in the form of energy head, which results in a higher pressure immediately downstream from the propeller. Further downstream at the exit of the propeller, the flow condition is more stable, a slight drop in pressure head may result from both the head loss between Sections 1 and 2 and a slight increase in mean stream velocity. Therefore, the total energy head  $H_p$  is computed by using the equation,

$$H_p = \frac{u_o^2 - u_i^2}{2g} + \frac{p_d - p_u}{\gamma} \quad (18)$$

The output power may be expressed as

$$P_o = \gamma Q_f H_p = (\gamma Q_f) \left[ \frac{u_o^2 - u_i^2}{2g} + \frac{p_d - p_u}{\gamma} \right] \quad (19)$$

where  $\gamma = \rho g$ . In Eq. (19),  $\rho$  is the density of air in  $\text{kg/m}^3$ ,  $p_u$  is the upstream pressure of air of the propeller in  $\text{kN/m}^2$  and  $V_i$  is the velocity of air in m/s,  $Q_f$  is the volume flow rate of the air in  $\text{m}^3/\text{s}$ ,  $p_d$  is the downstream pressure of air of the propeller in  $\text{kN/m}^2$  and  $u$  is the velocity of air in m/s at the Sections 1.1 and 2.2 of the propeller as shown in Fig. 4, respectively. The volume flow rate  $Q_f$  and the clearance height  $h$  can be calculated by using the general equation:

$$Q_f = Av_c = hL_c D_c v_c = hL_c D_c \sqrt{\frac{2p_c}{\rho}} \quad (20)$$

$$h = \frac{Q_f}{L_c D_c \sqrt{\frac{2p_c}{\rho}}} = \frac{Q_f}{k\sqrt{p_c}} \quad (21)$$

where  $k = L_c D_c \sqrt{\frac{2}{\rho}}$ ,  $h$  is the theoretical clearance height of the air-cushion in m,  $L_c$  is the air-cushion perimeter in m;  $D_c$  is the discharge coefficient, and  $\rho$  is the air density in  $\text{kg/m}^3$ . Therefore, the additional thrust  $F_{tac(add)} = R_{drag}$  could be computed as

$$F_{tac(add)} = \frac{\rho Q_f}{r_o \omega} \left[ \frac{u_o^2 - u_i^2}{2g} + \frac{p_d - p_u}{\gamma} \right] = R_{drag} \quad (22)$$

Fig. 5 shows the Sepang peat terrain in Malaysia. The bearing capacity of swamp peat in Malaysia is considered as  $5 \text{ kN/m}^2$  and surface mat thickness of 50 mm has been considered in this study. Wong et al. [7] reported that the surface mat of the peat or muskeg of the terrain allows the vehicle to travel rather than that the vehicle sinking. The swamp peat terrain parameters:  $\omega$  is the moisture content in percentage,  $c$  is the cohesiveness in  $\text{kN/m}^2$ ,  $\varphi$  is the internal frictional angle in degrees,  $K_w$  is the shear deformation modulus in m,  $m_m$  is the surface mat stiffness in  $\text{kN/m}^3$  and  $k_p$  is the underlying peat stiffness in  $\text{kN/m}^3$ , are shown in Table 1. As the mechanical properties of the swamp peat terrain are very difficult to measure and are not available. In this study the swamp peat terrain are considered as 50% worse than the peat terrain parameters of Sepang as stated by Aatur et al. [17]. The vehicle loading conditions of 2.45 kN and 3.45 kN and the travelling speed of 10 km/h are considered for the study of vehicle design parameters. The simulation on the vehicle design parameters and performance are conducted by using the MATLAB and MS Excel.

The acceptability of the vehicle is verified by the simulation in both moderate peat terrain and swamp peat terrain. The moderate peat terrain bearing capacity of  $12 \text{ kN/m}^2$  is reported by Aatur et al. [15] and swamp peat terrain with a bearing capacity of  $5 \text{ kN/m}^2$  is reported by Jamaluddin [12]. The vehicle's total ground contact area considered as  $1.052 \text{ m}^2$  including  $0.544 \text{ m}^2$  of air-cushion system area were optimized based on the bearing capacity of the terrain. The vehicle tracked ground contact area  $0.508 \text{ m}^2$  is optimized for operating on the moderate peat terrain without activating the air-cushion system.

Fig. 6 shows the relationship between the vehicle's tractive effort and motion resistance. The result shows that the vehicle is able to traverse the terrain as the vehicle total tractive effort is more than the vehicle's total motion resistance which is mainly due to the terrain compaction and



Fig. 5. Photo of Sepang peat in Malaysia.

Table 1  
Terrain parameters.

Parameters	Un-drained	
	Sepang Mean value	Sarwak Mean value
$\omega$ (%)	90.51	98
$\gamma$ (g/cm <sup>3</sup> )	0.082	0.045
$c$ (kN/m <sup>2</sup> )	0.78	0.38
$\phi$ (degree)	12.64	20
$K_w$ (cm)	0.635	1.24
$m_m$ (kN/m <sup>3</sup> )	14.42	7.42
$k_p$ (kN/m <sup>3</sup> )	119.65	59.65

Source: Ataur et al. [15].

air-cushion system dragging. The track system is unable to develop sufficient tractive effort to overcome the motion resistance and this could be for the lower cohesiveness ( $c$ ) and internal friction angle ( $\phi$ ). For the vehicle ground contact area of 1.052 m<sup>2</sup>, the tracked system only developed 0.49 kN tractive effort while the additional 0.54 kN tractive effort was developed by the propeller. Therefore, it could be concluded that the vehicle can traverse the swamp terrain with the help of the air-cushion system.

Fig. 7 shows that the individual motor needs 0.90 kW power to develop the sufficient torque to the individual sprocket develop 0.49 kN tractive effort to the tracked system. Meanwhile, the propeller needs 1.80 kW to develop the 0.54 kN additional thrust for the vehicle to traverse the terrain. Therefore, the vehicle needs to select a battery pack which is able to supply 3.40 kW for 2 h during traversing the swamp peat terrain.

Eight (8) batteries are arranged in the battery pack in order to power the motor of the tracked system and propeller motor. It is noted that the vehicle was initially operated for 2 h with the power of the battery pack.

In the earlier study it is reported that the bearing capacity of the swamp peat is 5 kN/m<sup>2</sup> which could be the nominal ground pressure (NGP) of the terrain. Fig. 8 shows the GNP is lower than the 5 kN/m<sup>2</sup>. Furthermore, Fig. 8 shows the importance of the air-cushion system for the vehicle potentiality over the swamp terrain. Vehicle ground pressure for the 2.45 kN and 3.43 kN are more than the nominal ground pressure of the terrain. Therefore, the vehicle would not traverse over the swamp terrain. By equipping air-cushion system of contact area 0.544 m<sup>2</sup>, the vehicle is fit to traverse on the terrain. Fig. 8a shows that the vehicle ground contact pressure (VGP) is higher than the nominal ground contact pressure (GNP). Ground nominal pressure is defined as the pressure that exists from the ground with respect to the static or dynamic load of the vehicle on that ground. Meanwhile, the vehicle ground contact pressure is defined as the pressure that distribute to the ground with the ground contact area of the vehicle. Result showed that the VGP-without the air-cushion is always higher than the GNP. It is noted that the vehicle will sink if  $P > P'_0$  and it is also supported by Ref. [10]. Therefore, the air-cushion system is attached to the vehicle in order to maintain the vehicle sinkage and ground contact pressure. By distribut-

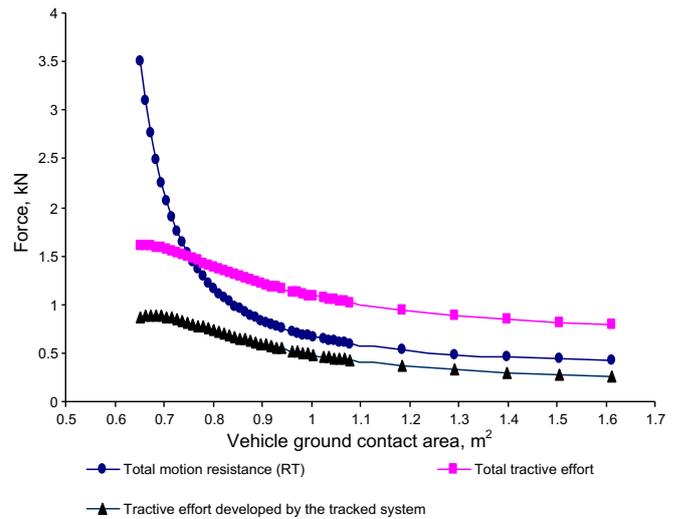


Fig. 6. Relationship between the force and the motion resistance for the vehicle weight = 3.43 kN.

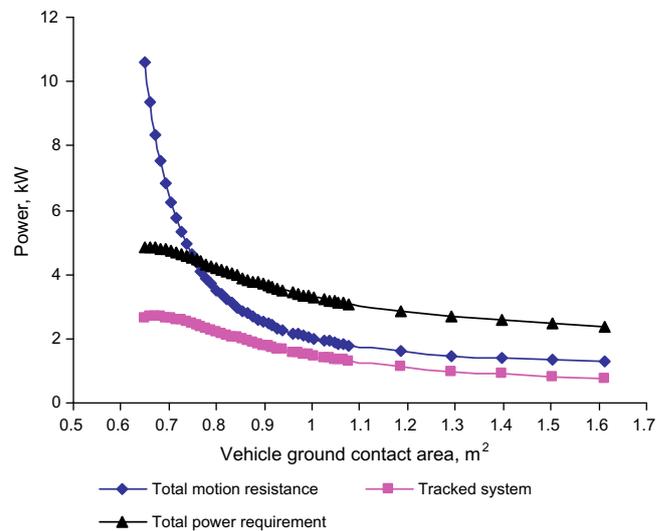


Fig. 7. Power requirement for propelling the vehicle weight = 3.43 kN.

ing the load to the air-cushion system, the vehicle ground contact pressures turn to 2.33 kN/m<sup>2</sup> for the 2.45 kN vehicle and 3.26 kN/m<sup>2</sup> for the 3.43 kN vehicle which are lower than GNP for the respective vehicles. The load distribution to the air-cushion system is defined as the load transferred from the tracked system to air-cushion system in order to limit the vehicle sinkage and to maintain the vehicle ground contact pressure which could be less than 5 kN/m<sup>2</sup>. The load distribution is computed in this study by using the equation,  $W_{ac} = 2(VPG - NGP)(LB)$ , where  $W_{ac}$  is the distributed load to the air-cushion system, kN. The GNP is computed by using

$$P = \left( k_p z + \frac{4}{D_h} m_m z^2 \right) \text{ with } D_h = D_{ht} + D_{hc},$$

$$D_{ht} = \frac{4B_t L_t}{2(L_t + B_t)} \quad \text{and} \quad D_{hc} = \frac{4B_c L_c}{2(L_c + B_c)}$$

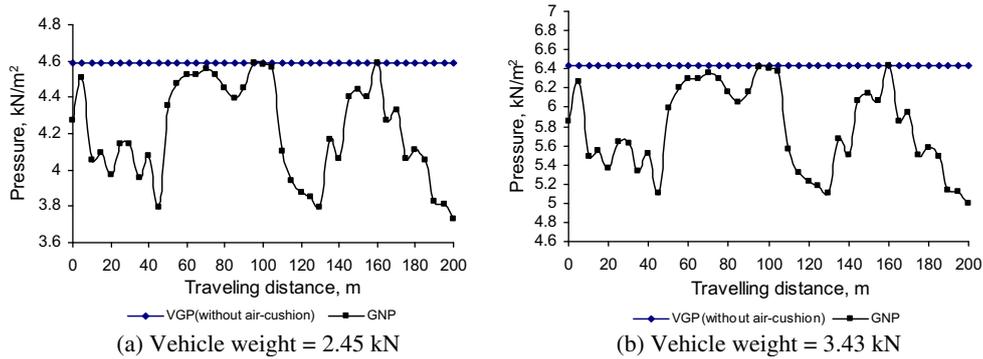


Fig. 8. Variation of the vehicle ground contact pressure (VGP) and ground nominal pressure (GNP).

where  $L$  and  $L_c$  are the contact length of the track and cushion system while,  $B_t$  and  $B_c$  are the width of the tracked and cushion system, respectively. By using the terrain parameters  $k_p$  and  $k_c$  as shown in Table 1 for Sarawak terrain, the  $P$  (i.e., GNP) is computed.

Fig. 9 shows the load distribution to the air-cushion is all over the vehicle's travelling path. The power consumption of the propeller depends on the load distribution to the air-cushion system. The maximum power requirement of the propeller motor: 1.28 kW for the 2.45 kN vehicle and 2.2 kW for the 3.43 kN vehicle. As the vehicle is powered by the battery pack, emphasis is given to less load distribution to the air-cushion system which is operated with the developed additional thrust of the propeller and the propeller motor consumes 50–64% of the total power of the battery pack.

Fig. 10 shows the designed and developed HETAV. Steering of this vehicle was achieved by means of an individual switch of the DC motor with a power of 0.500 kW @ 2.94 N m. The dry weight of the vehicle equals 2.45 kN. The vehicle is designed mainly for operating a maximum load of 3.45 kN including a 1.00 kN payload over the swamp peat terrain. The total ground contact area of the vehicle is 1.052 m<sup>2</sup> including 0.544 m<sup>2</sup> of the air-cushion system. The vehicle is powered by a battery pack comprising eight (8) lead acid batteries, connected in parallel. The vehicle can travel 24 km powered of the single charging battery pack. A small IC Engine power of

2.5 kW @ 4000 rpm is installed on the vehicle to recharge the battery pack with the help of an alternator. The vehicle is controlled by a remote control system from the road side in order to avoid the risk if there is any.

### 3. Results and discussion

#### 3.1. Laboratory test

The vehicle was tested outside on the field of the Faculty of Engineering, IIUM at travelling speeds of 10 km/h and



Fig. 10. Photo of the vehicle.

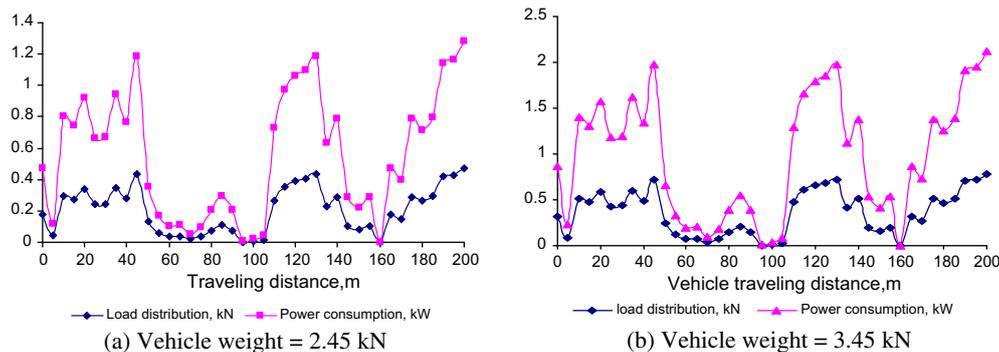


Fig. 9. Affect of load distribution of air-cushion on the vehicle power consumption.

15 km/h with loading conditions of 2.45 kN and 3.45 kN with and without activating the air-cushion system. The vehicle travelling distance during testing was considered as 50 m. The output torque of the DC motor was measured and it was converted into tractive effort. The motion resistance test was performed by pulling the vehicle with an auxiliary vehicle. It is noted that a load cell was placed in between the tested and auxiliary vehicle. Data were recorded from the load cell every 5 s. The vehicle was found to have much potential to travel over the grass field without the air-cushion. However, it was stuck once the air-cushion contacts with the terrain. By using the propeller additional thrust it was operated without getting stuck. Figs. 11 and 12 show the typical variations of tractive effort and motion resistance of the HETAV.

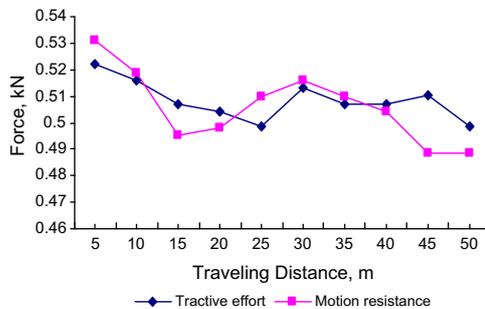
The results show that the mean value of traction with a propeller over the without a propeller increases 10.21% and 6.47% for the vehicle weights of 2.45 kN and 3.43 kN, respectively. Similarly, it was found that the motion resistance decreases 12.63% and 24.81% for the vehicle weights of 2.45 kN and 3.43 kN, respectively. It is concluded that the increment and decrement of the tractive effort and motion resistance were due to the additional tractive effort developed by the propeller. Furthermore, the mean value of tractive effort increases is mainly due to the increment of the loading conditions of the vehicle as the cohesiveness of the field is approximately constant for all the travelling length. The conclusion is also supported by the conclusion remarks of Wong [8], Yong et al. [9], and Ataur et al. [14].

### 3.2. Field test

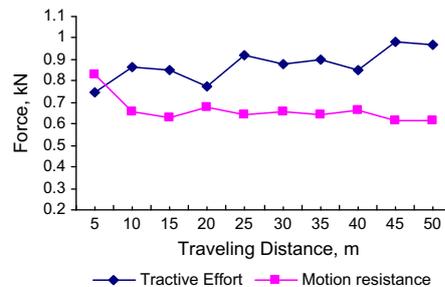
The field experiment was conducted on the terrain of length 50 m which was made similar to swamp peat just on the river side of the International Islamic University Malaysia. Figs. 13 and 14 show the typical tractive effort of the HETAV. Results shows that the mean values of traction are 0.62 kN and 0.72 kN for the 2.45 kN vehicle at the travelling speeds of 10 km/h and 15 km/h, respectively. Meanwhile, the mean values of traction are 0.90 kN and 1.06 kN for the 3.43 kN vehicle at the travelling speeds of 10 km/h and 15 km/h, respectively. With the vehicle travelling speeds from 10 to 15 km/h, the mean value of traction increases 16.13% for the 2.45 kN vehicle and 15.09% for the 3.45 kN vehicle. This could be due to the hydrodynamic effect of terrain [7,13] as there is no drainage system in the field. Furthermore, with increasing the vehicle loading conditions from 2.45 kN to 3.45 kN, the mean values of the vehicle traction increases 45.16% for the speed of 12 km/h and 47.22% for the speed of 15 km/h. This is mainly due to the loading condition of the vehicle as the cohesiveness of the field is approximately constant all over the terrain.

### 4. Conclusions

The following conclusions are reached based on the discussion of this study:

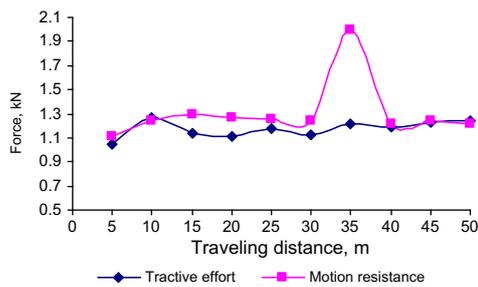


(a) Operating with air-cushion

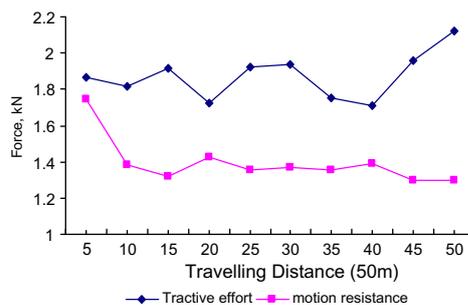


(b) Operating with air-cushion and propeller

Fig. 11. Variation of tractive effort and motion resistance for the vehicle weight = 2.45 kN at 10 km/h.



(a) Operating with air-cushion



(b) Operating with air-cushion and propeller

Fig. 12. Variation of tractive effort and motion resistance for the vehicle weight = 3.43 kN at travelling speed of 10 km/h.

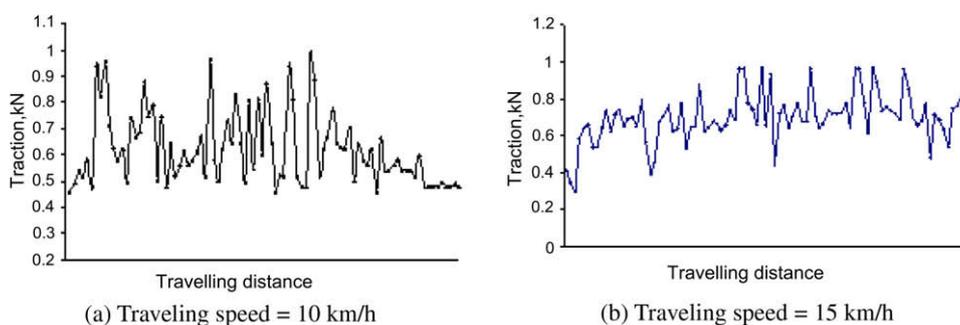


Fig. 13. Variation of traction for the vehicle weight = 2.45 kN.

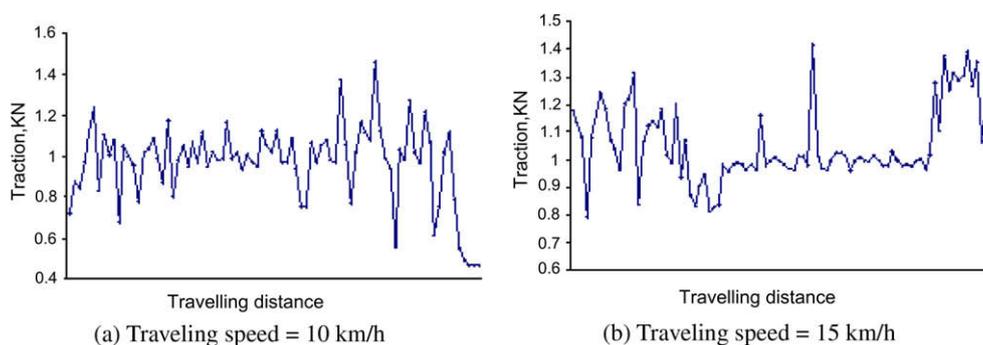


Fig. 14. Variation of traction for the vehicle weight = 3.45 kN.

1. The air-cushion was activated as soon the vehicle sinkage was closed to 0.05 m.
2. Based on the simulation results the following conclusions could be drawn:
  - (i) The vehicle must develop 1.4 kN in order to traverse the swamp terrain without any risk.
  - (ii) The air-cushion system of the vehicle makes the vehicle ground contact pressure less than 5 kN/m<sup>2</sup> for traversing partially supporting the vehicle load and could make the vehicle of great potential for traversing the terrain.
  - (iii) The ground nominal pressure which could be equivalent to the terrain bearing capacity was found in the simulation to be less than the reported bearing capacity of swamp terrain by MARDI. It could be the considered 50% worse terrain condition of Sepang.
3. The battery pack was provided to power the vehicle for travelling at least 15 km with a single battery charging.
4. Based on the experimental results:
  - (i) The mean values of the vehicle's tractive performance in terms of tractive effort and motion resistance, indicate that the vehicle would not be able to traverse the swamp terrain without an air-cushion and the additional thrust of the propeller.
  - (ii) The mean value of the tractive effort of the vehicle increases with increases in the vehicle loading conditions, which could be due to the changing of the track ground contact area. Since the track width is constant, the track ground area is the function of the track ground contact length, i.e.,  $A_t = \oint(L)$ , where  $L = (L_{XY} \cos \theta + L_{YZ} + R_{rs} \sin \theta)$  and as well as vehicle weight.
  - (iii) The traction coefficient of the vehicle is in the range of 77–85% which makes the vehicle of great potential to operate on the swamp peat terrain.
  - (iv) It is not possible to limit the vehicle sinkage at 70 mm if the vehicle is not equipped with an air-cushion system. Furthermore, the vehicle will get stuck in the swamp terrain if it is equipped with an air-cushion without a propeller as the dragging motion resistance of the air-cushion system is considerable high. Therefore, the vehicle must be equipped with an air-cushion system and propeller in order to operate on the swamp terrain without any difficulties.
  - (v) The novel-design-air-cushion supporting system makes the vehicle more vulnerable to operate on the real swamp peat as it allows the vehicle to traverse any unprepared terrain by adjusting the air-cushion automatically by absorbing the longitudinal and vertical displacement.

### 5. Future research

The author is developing a full-scale vehicle is made by adopting the same concept and would like to test it in the real swamp peat in Sarawak, Malaysia which is 1000 km away from the Kuala Lumpur. The statistical analysis will be conducted in order justify the vehicle mobility.

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