A NOVEL DRIVE SYSTEM TO IMPROVE THE EFFICIENCY OF INDOOR TRANSPORTATION VEHICLES

Utkarsh Ranjan, Pulkit Jain, Lokesh Dutt and Manish Singh Bisht
Department of Mechanical Engineering, College of Technology, Govind Ballabh Pant University of Agriculture & Technology, Pantnagar City, Uttarakhand

ABSTRACT
Indoor transportation vehicles play a critical role for physically impaired, however they may have an even wider scope of application, from an inter-industrial transportation vehicle to a human transporter. A simple indoor transporter has been modified by a hybrid drive system, by combining the characteristics of an air cushion vehicle and a simple electric- motor vehicle. The paper contains design and simulation of an indoor vehicle for a design load of 100 kg. Various weight distribution ratios were tested to find the best performance on account of power consumed and handling characteristics. It was found that a weight distribution ratio of .5 was suitable for concrete platforms, with a maximum reduction of about 53% in power consumption. The vehicle constituted a bag skirt and two centrifugal air blowers for air cushion creation, with two wheels for propulsion and handling, powered by two electrical D.C. motors (geared) via a switch mode power supply. Later a caster wheel was added for stabilising uneven loading which created vibrations during acceleration and breaking. Various types of floors were tested to measure tire slippage and rolling friction, for a maximum speed of 16 km/h. All theoretical results were confirmed by ammeter and voltmeter readings taken in practical experiments.

KEYWORDS: *Wheeled air-cushion vehicle, Low speed transportation system, Hybrid-Electric motor drive, Variable Load distribution vehicle.*

I. INTRODUCTION

With the growing popularity of segways, the concept of locomotion has been redefined. As indoor places are growing bigger, there has been a need for efficient human transportation systems. The conventional transporters include either a one wheeled or a multiple wheeled configurations, with most of them being electrical vehicles, based on conventional drive systems. A recent development of semi tracked/wheeled vehicles have been found very successful in military vehicles, especially for loose or sandy terrains or those soils with a low angle of cohesion. The important feature of these vehicles is load distribution, in between surface contained devices such as tracks or wheels and an air cushion. The main advantage of distributing weight is that it can have a variable traction force and there is a great reduction in rolling resistance, hence net resistance is also reduced. Variable traction in wheels allows the vehicle to have good start-up characteristics, which can be suitably adjusted according to the surface friction and adhesion. A similar vehicle has been very effective for transporting heavy equipment; an air-cushion trailer is very commonly used in industries for transporting very heavy objects. Our main objective was to fabricate a vehicle that is light in weight, with very low power consumption. As it uses weight distribution, weight on the skeleton/frame is reduced significantly, hence allowing us to use less material in its construction, by supporting it with a skirt with a significant dynamic pressure. The only problem with such hybrid drive systems is that, the skirt must be stiff before it is loaded, otherwise the frame might not be sufficiently stable.
Further on its advantages, it significantly uses less power for use, with a hybrid drive, it can be about 50% more efficient than conventional system, and however it may be a bit noisy dude to air

compression and expansion, with little vibrations generating in the frame. It's turning radius is determined by the weight distribution ratio, a lesser amount of load on tires would mean a bigger turning radius, as we decrease the force on air film, and the turning radius gets smaller. In comparison to a conventional Hover craft or ACVs, it has very good turning characteristics; however it has a bigger turning radius in comparison to a wheeled drive system. Moreover a lower centre of gravity was possible, hence there is more stability in operation of control, however it has a low clearance, thus it is appropriate for smooth floors indoors, for efficient operation.

II. DESIGN FACTORS

As mentioned previously, the introduction of flexible skirts permits a considerable reduction of clearance height, and hence power for lift. It should be pointed out, however, that the reduction of clearance height would likely increase the skirt contact drag, thus increasing the power for propulsion. Apparently, a proper balance between the reduction of lift power and the associated increase in propulsion power has to be struck to achieve a minimum total power requirement.

2.1 Momentum Drag

To sustain the cushion, air is continuously drawn into the cushion system. When the vehicle is moving, the air is effectively accelerated to the speed of the vehicle. This generates a resisting force in the direction of the air relative to the vehicle, which is usually referred to as the momentum drag *R.* The momentum drag can be expressed by [1]
Where V_a, is the speed of the air relative to the vehicle and Q is the volume flow of the cushion system. This momentum drag is unique to air-cushion vehicles. It should be noted that part of the power to overcome momentum drag may be recovered from utilizing the dynamic pressure of the airstream at the inlet of the fan to generate the cushion pressure. The dynamic pressure of the airstream at the intake of the fan p_d is given by [1]-

$$p_{d}=.5\rho V_a^2 \quad (1)$$

Assume that the efficiency of the cushion system including the fan and ducting is η_{cu} then the power that can be recovered from generating the cushion pressure is given by [1]

$$P_r=.5\eta_{cu}\,\rho Q V_a^2 \quad (2)$$

2.2 Rolling resistance

Skirt contact drag, aero dynamic drag and trim drag can be neglected due to its restricted application indoors, on flat surfaces with low speed. However, a new type of resistance force appears due to the interaction of wheels with the ground. Weight distribution is a necessary factor here, rolling resistance increases as weight on wheels increases, although it helps in improving the turning characteristics of the vehicles. Hence a suitable ratio has to be selected in order to have better power efficiency and good handling characteristics as well. Rolling resistance [2] is defined by R_{r}-

$$R_r = A_G\,(D_L - P_d\,S_C)^{(2n+2)/(2n+1)} \quad (3)$$

Where A_G depends on the type of surface, D_L is the design load, n be the soil deformation index and P_d and S_C be the effective skirt pressure and effective area of the skirt.
Power required to overcome rolling resistance will be denoted as P_{rr}, is a product of linear velocity and rolling resistance hence,

$$P_{rr}= R_r V \quad (4)$$

Where V is the velocity of the vehicle

2.3 Total resistance and power lost

Total resistance is defined as *R*, where *R* is the sum of moment drag and rolling resistance,

Hence, $R = R_{m}+ R_r$

Total power lost in overcoming resistance, P_T is the sum of rolling resistance and Momentum drag, Henceforth,

$$P_T = P_{rr} + P_r = .5\eta_{cu}\,\rho Q V_a^2 + R_r V \quad (5)$$

The design consideration includes minimization of resistive forces and the total power lost in overcoming these forces.

2.4 Design load

Design load is the total weight for which the vehicle can operate without any risk of failure.
It can be defined as D_L, which is a function of effective skirt area (S_C) and pressure created in the skirt (p_d).
Effective pressure in the skirt is given by

$$p_{d}= .5\rho V_a^2 \tag{6}$$

Now total load carrying capacity of the skirt is the product of effective skirt area and effective pressure, which is given by D_{CL},

$$D_{CL} = S_C\,(.5\rho V_a^2) \tag{7}$$

Considering the Weight distribution factor on air cushion as to wheels as k, hence total weight bearing capacity of the wheels is defined as D_w,
Where,

$$D_w = (1-k)D_{CL} \tag{8}$$

Hence total design load,

$$D_L = D_{CL} + D_w \tag{9}$$

Therefore, it can be written as,

$$D_{L} = D_{CL}\,(2-k) \tag{10}$$

2.5 Blower specifications and air film clearance

The air film thickness is determined by the volume of air pumped in the skirt per second; the greater the flow rate of air, greater will be the dynamic air film.
Let v flow rate of the air blower, then considering an effective area of S_C,
For a total air film thickness t,

$$t= v/S_C, \tag{11}$$

2.6 Motor drive and wheels

Motor specifications play a key role in propulsion; geared D.C. motors are the best option for consideration. The main drawback is the operation speed of the motor, in order to have efficient use of it, it should be operated in the range of its design specification, and hence a gear box is a necessary requirement.The motor should have high torque and low rpm, to easily facilitate the movement. In order to produce movement, the radius of the wheels was such that it should synchronize with the air film, according to the desired load distribution factor k.
Let T be the torque generated by the motor, then for a weight distribution ratio k, design load on the wheels is has been mentioned as,

$$D_w = (1-k)D_{CL} \tag{12}$$

Hence, for a wheel radius r, the motor should work without any slipping on a surface with coefficient of friction f, for a torque T related as

$$T=f\,rD_w \tag{13}$$

2.7 Centre of Pressure

An air cushion vehicle must be well-balanced in order to operate properly. If not correctly balanced, one side of the skirt will lift off the ground while the other will not budge. To insure proper weight distribution, the centre of mass of the craft must be at the centre of pressure.

III. PERFORMANCE FACTORS

2.1. Turning characteristics

As discussed earlier turning characteristics depend on the weight distribution factor k, a design speed of 16 km/h was considered, and the following results can be achieved [1]

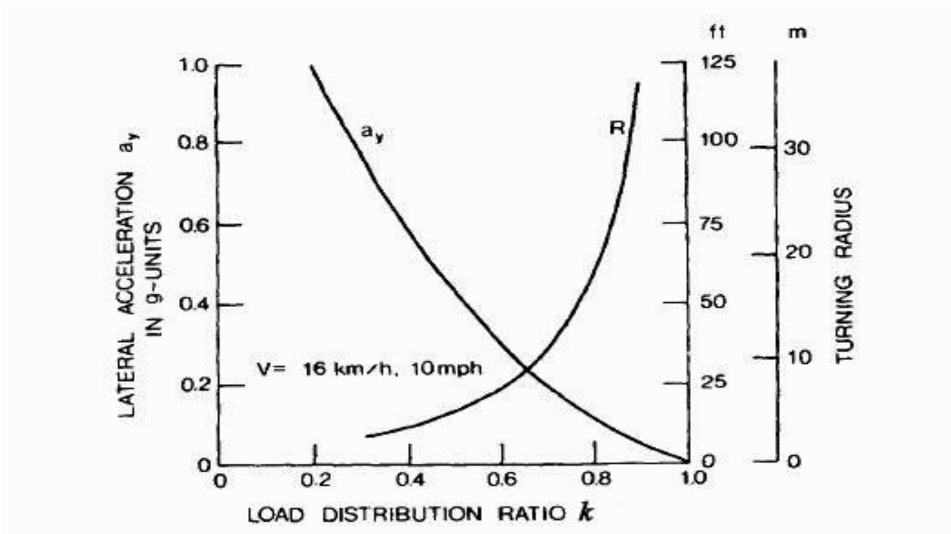

Figure 1. Turning characteristics, as per change in acceleration and load distribution ratio

It can be seen from the figure, the most suitable load distribution factor is around .7, and however the turning radius corresponding to this value is not suitable for indoor applications, hence, for the maximum design velocity of 16 km/h, a weight distribution factor of .5 was chosen, corresponding to that a turning radius of 5 m was chosen, moreover the vehicle was able to have a zero turning radius at very slow velocities.

2.2. Power consumption

As rolling resistance is significant in wheeled vehicles, and by introducing aircushion support, rolling resistance has been halved, moreover the required torque on the motor, to move the vehicle is also halved for *k* equal to .5, and so is the power consumption.
Power requirement as related to *k*,

$$P= (1-k)T\omega \tag{14}$$

Where, ω is the angular velocity of the wheel.

2.3. Weight distribution factor vs. turning characteristics

For minimum power loss, power saved by weight distribution should be at least equal to the losses generated through momentum drag and duct losses, assuming aerodynamic drag to be negligible, then

$$P_{rr}= P_r \tag{15}$$

k_{max}, can be defined as the most efficient weight distribution factor

$$k_{max} =D_{CL}/[(P_r/V)^{.5}+ D_{CL}] \tag{16}$$

Where, k_{max} is a fraction which decreases as the design load increases, hence considering the handling characteristics, such a hybrid drive is optimal for lifting heavy loads totally fir for industrial use.
For a vehicle designed for a design load of 100 kg, k_{max} is about .9 which will result in poor handling characteristics; hence for almost all practical purposes, *k* should be decided according to the turning characteristics curve, although it may not be the most efficient option.

IV. DESIGN SIMULATION

3.1. Mathematical modelling

The first objective was to develop the equations of motion to represent the hybrid air cushion vehicle. With the equations of motion determined, parameters of this particular situation could be evaluated. Certain parameters can easily be measured, but others require estimation. Once completed, the system could be placed in Matlab and Simulink and simulations were evaluated.
State-space models represent the dynamics of physical systems described by a series of first order coupled differential equations. In the general state-space model, x is the state vector and y is the output. The set of equations are given by[3] :

$$\dot{x} = Ax + Bu \qquad (17)$$
$$y = Cx + Du \qquad (18)$$

The vector x is of dimension n by 1 containing the state variables which often represent position and velocity. The matrix u represents the input variables, usually forces in mechanical systems. The remaining matrices, A, B, C, and D, determine the relationships.
Open-loop simulations are simulations run without any feedback; no control is placed on the system. Closed-loop simulations are those run with feedback with the aim of controlling the system. One example of a closed loop system is a rocket launch: as position/velocity/orientation changes, these values are fed back into the system with the appropriate gains to create a straight flight path.
Let A be n-by-n matrix of complex or real numbers. $\lambda \in$C is an eigen-value of A with eigenvector v $\in C^{n}$ if v is not zero and Av □ $\lambda\ v$. Eigen-values can be used to determine the stability of a system. Eigen-values in the open right half of the complex plane indicate instability; in the open left half plane they signify stability. When lying on the imaginary axis they indicate a marginally stable system. Linear approximation allows nonlinear mechanical systems to be analysed with tools used for studying linear systems. Nonlinear systems can be linearized around an operating point of interest and their local stability analysed. [4]

3.2. Simulink assumptions

The test vehicle was assumed to have inertial properties of a disc and the condition of pure rolling to be true throughout the simulation. The weight of the vehicle with person has been assumed to be about 120 kg; with a total skirt area of 2 m^2 has been calculated corresponding to the required air pressure generated by the blower. Further, the shape of the skirt has been assumed to be a vertical cylinder. The initial velocity (at t=0) is assumed to be 2 metres/second in x direction.

3.3. Simulink model

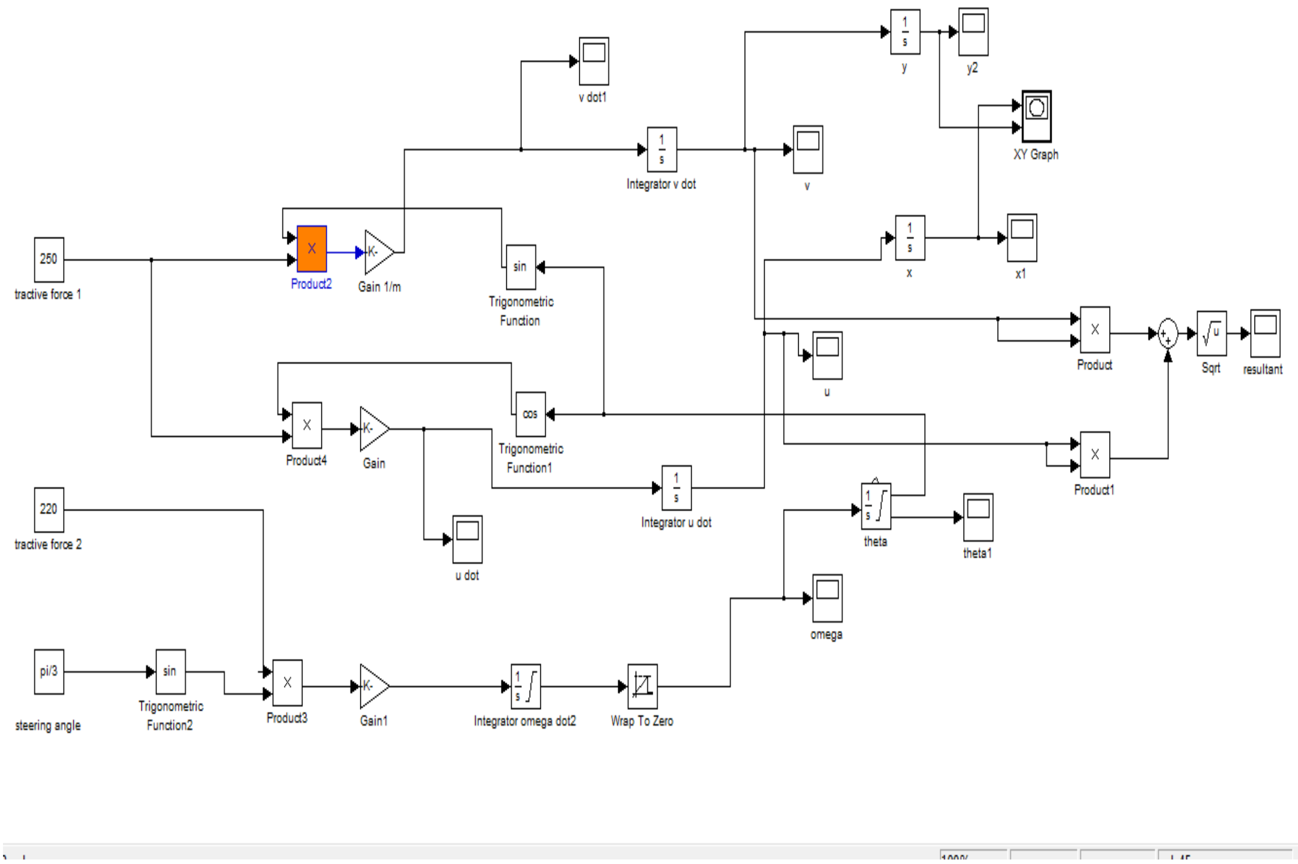

Figure 2. Simulink model considering design load

3.4. Simulation results

As per design conditions for a design load of 100 kg for a load distribution factor of .5, stable turning characteristics were achieved. The tuning characteristics depend on the initial speed of the vehicle, power of the motor and the shape and inertial properties of the vehicle, as per the test model, following turning trajectory was achieved for an initial speed of 2 m/s with a 250 watt motor consideration, with an angular speed of 300 rpm for a 120 degree directional change the following trajectory was achieved. The turning radius was found to be about 5 meters as per the simulation

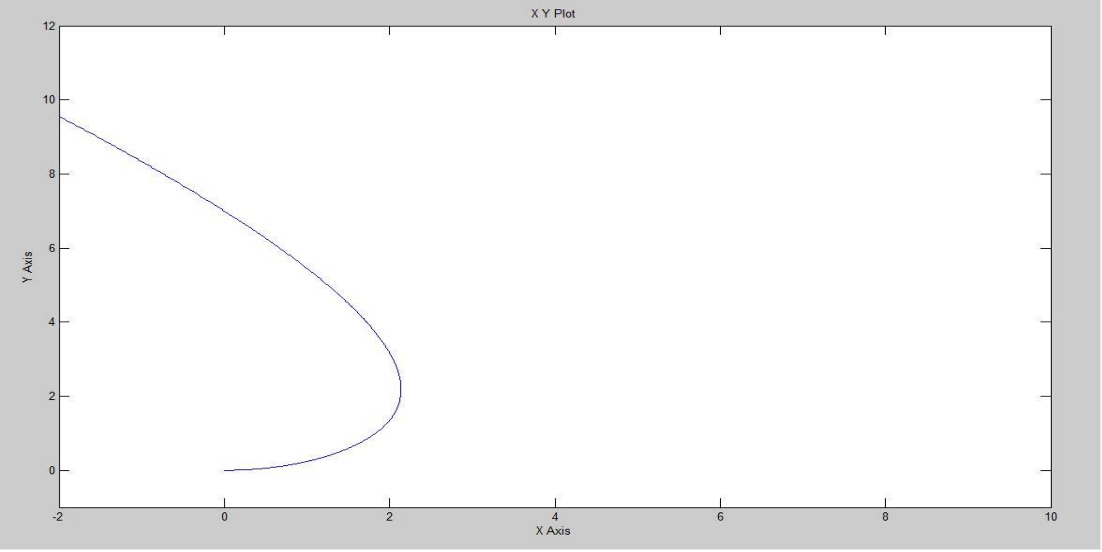

Figure 3. Turning radius estimation

V. THE TEST MODEL

The test model was based on a simple bag skirt with an area of about 2 m^2, with a wooden platform to support motor clamps and the blowers. Each motor was a 24 V, D.C. motor with a max current input of 2 Amperes, and each blower was rated as 650W, 220 V and 1.7 Amperes, all experiments were performed by putting dead weights on this model.

Figure 4. Final test model

VI. Conclusions

A significant reduction in the power consumption was achieved as per propulsive effort, moreover resistive forces have been significantly reduced. The weight distribution factor *k* plays the key role in performance, for very heavy vehicles, highest efficiency is achieved; however the turning characteristic curve is a much more suitable criterion for the estimation of *k* as it greatly determines the turning radius and manoeuvrability. Hence for practical purposes a minimum power reduction of 50% was achieved which is about 150 % more efficient than the conventional tire or tracked drive.

VII. Acknowledgements

We wish to express our profound sense of gratitude and indebtedness to Dr. Anadi Misra, Professor in Department of Mechanical for imparting valuable guidance, help rendered to us during fabrication work and unstained encouragement rendered during the various phase of work. We would like to thank him for having confidence is us and trusting us in what we did. We would also like to thank Tirath Singh and Virendra Singh Chulkotiya for helping us in fabricating the test model and making all the things needed to be available to us at great times of need. Here's big "Thank You" to all those who we involved in this project directly or indirectly and making this project a great success.

References

[1]. Theory of ground vehicles I J.Y. Wong.-3rd ed. Page 497-498, 519.
[2]. Int. J. of Vehicle Design Vol. 31, No. 1, 2003. 112. Design of a novel semi-tracked air-cushion vehicle for soft terrain. Zhe Luoy, Fan Yu* and Bing-Cong Chenz
[3]. Hovercraft Kinematic Modeling, Lindsey Hines and Dr. Michael P. Hennessey Center of Applied Mathematics ,University of St. Thomas.
[4]. Multi-Domain Modeling of the Dynamics of a Hovercraft for Controller Development Terry Denery, PhD, The Math Works, Natick, MA 01760.

Authors

Utkarsh Ranjan received his B. Tech degree from GBPUAT, Pantnagar, Uttarakhand, and his key areas of research are Control systems and Automobile Engineering.

Pulkit Jain received his B. Tech degree from GBPUAT, Pantnagar, Uttarakhand, he is currently a student at Central Mechanical Engineering Research Institute, Durgapur India.

Lokesh Dutt received his B. Tech degree from GBPUAT, Pantnagar, Uttarakhand, and currently he is looking forward to pursue higher education from India.

Manish Singh Bisht received his B. Tech degree from GBPUAT, Pantnagar, Uttarakhand, and currently he is looking forward to pursue higher education.