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Development of the Performance Prediction Program of an Air Brake System

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Abstract — **Braking system being most important part of any vehicle shall be a primary consideration for vehicle safety. As braking system has to satisfy certain regulatory as well as implied needs of the customers. It is quite challenging to estimate the braking performance of a vehicle. braking system consists of many parts such as dual brake valve, brake boosters, spring brake actuators, S-cam brake etc. the effect of the characteristics of each part on the entire system has to be considered simultaneously. The performance mapping through actual brake test on vehicle requires much time & money. The development of a method to estimate the braking performance of a vehicle using qualitative methods is beneficial. In this study a program for 2-Axle truck equipped with an air brake system, that can analyze the braking capabilities of a vehicle, such as deceleration, stopping distance, pedal effort is presented. Output of the program is verified by comparing with brake test results conducted on a vehicle & co-relation between predicted & actual performance is established. This method will reduce number of design iterations as well as reduce the development time, cost & labor.**

***Keywords** — Regulatory requirements, Braking performance, Deceleration, stopping distance, pedal effort, adhesion utilization, partial failure, static & dynamic axle loads, optimum braking forces, Service brake, Secondary brake, Parking brake*

I. INTRODUCTION

The safe & reliable use of a vehicle on road necessitates the continual adjustment of its speed & distance in response to change in traffic conditions. This requirement is met in part by the braking system, design of which plays a key role in ensuring a particular vehicle is suitable for a given application. Thus Braking performance should be a primary consideration for vehicle safety. Braking system consists of many parts such as Pedal, brake valve. Brake chamber & actuators, wheel brakes. In order to design a system that satisfies braking performance requirements, the effect of characteristics of each part on the entire system has to be considered simultaneously. However predicting the braking performance through an actual test requires a lot of time, labor & cost. To overcome this, it is beneficial to develop a targeted program & apply it to design.

A great deal of research on braking performance has been done so far. Puleo (1970) studied the braking force distribution device while Limpert (1971, 1974) & Nakaura (1977) introduced theoretical & experimental approaches to calculate braking force distribution. Researches on the Anti-lock Braking System (ABS) & its ability to guarantee steering safety was investigated by multiple groups like Gatt (1977), Bisimis (1979), & Ivanov & Belous (2005). Bosch (2003), which developed automotive parts, researched ABS & introduced the vehicle position control theory supported by data obtained through experience & experiments. The prediction on braking performance of a vehicle using computers has also been investigated. Choi et al. (2004) researched braking distance with a finite element model of a tire. Hong & Huh (2004) examined methods that estimate braking force & road friction coefficient using a dynamic model of a tire of particular interest. Suh et al. (2001) developed a program to calculate the braking performance of a tractor-semitrailer vehicle. Kim & Rhim (1992) investigated the effect of pedal effort on the characteristics of brake devices. Jung & lee (2004) predicted the inclusive braking performance of a vehicle according to the variation of deceleration & pedal efforts.

In this paper, a program that can precisely estimate the braking performance of a vehicle & establish design data base is presented. This program is made for 2-axle trucks & buses equipped with an air brake system. It is easy to use, as all of the input & output data are coordinated into a Microsoft EXCEL format. The resultant data is presented in the form of graphs which are used to verify whether the braking performance of a vehicle satisfies the internal & external regulations or not.

II. PERFORMANCE CALCULATION THEORY

The force required to move a stationary body is greater than that necessary to keep a moving body in motion. This is because the friction in static is always more than that in motion. When the wheel brake is operated too strongly, a wheel is locked up because the friction between the tire & road surface equals the friction of motion. If the wheel brake is operated below this point, the wheel keeps rotating & the friction approaches the friction at rest. Basically braking force should not be larger than the friction force between a tire & the road surface. Therefore the maximum deceleration of a vehicle is the friction coefficient of the road surface. This friction coefficient between road surface & tire is also called as traction coefficient. This traction is finite. Ideal brake system ensures the optimum utilization of the available traction while braking the vehicle. There are three basic intended functions of any brake system of a vehicle as 1) Decelerate or stop the vehicle in a controlled & repeatable fashion 2) Maintain vehicle speed during downhill operation 3) Hold a vehicle stationary on a flat or a gradient when parked. These basic functions have to be performed during normal operation of the brakes & to a lesser degree of braking effectiveness during partial failure.

A. *Ideal Brake force & brake torque calculation*

In order to calculate the ideal braking force, the change in the dynamic weight of a vehicle according to deceleration should first be calculated. During braking, in comparison with static weight distribution, the front axle weight increases while rear axle weight decreases. The dynamic weight distribution of a vehicle according to deceleration is shown in figure 1

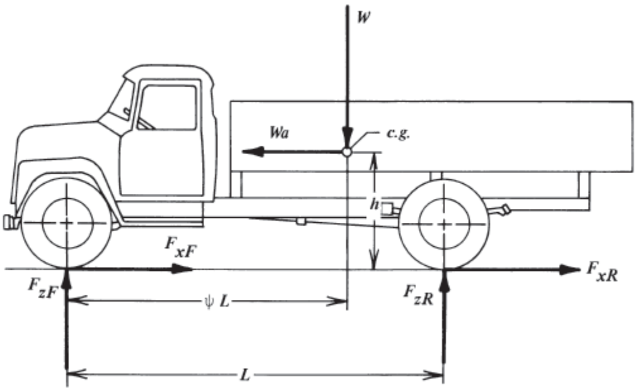


Figure 1. Dynamic axle load distribution

Equation 1 & 2 shows dynamic axle weights.

$$F_{ZF,dyn} = F_{zF} + [(h/L)\ a]\ w \qquad (1)$$

$$F_{ZR,dyn} = F_{zR} - [(h/L)\ a]\ w \qquad (2)$$

Ideal braking force with respect to axle weight is as follows.

$$F_F = F_{zF,dyn} * a \qquad (3)$$

$$F_R = F_{zR,dyn} * a \qquad (4)$$

Ideal braking torque is as follows

$$T_{Fi} = F_F * R_R \qquad (5)$$

$$T_{Ri} = F_R * R_R \qquad (6)$$

B. *Actual Brake force & brake torque calculation*

The actual brake force developed by the S-cam drum brake is given as below

$$F_x = (P_l - P_o)*A_c*\ \rho \qquad (7)$$

The actual Brake torque developed by the S-cam drum brake is given a below

$$T_a = (P_l - P_o)*A_c*\ \rho * BF * r \qquad (8)$$

ρ is called as mechanical gain & it is defined as the ratio of slack adjuster length & S-cam effective radius

BF is called as brake factor & it is defined as the ratio of total drum drag force to the application force

C. *Tire-road friction utilization (Adhesion demand)*

Several different variations of basically the same physical concept have been used to describe how close the actual braking force is to the optimum.

The tire-road friction utilization which is also called as adhesion demand, relates the maximum wheels unlocked deceleration to the lowest tire-road friction coefficient with which the deceleration can be achieved. It is the ratio of actual brake force to the dynamic normal force on particular axle brakes.

For a 2-axle vehicle having fixed brake force distribution, the adhesion demand for front axle brakes is calculated as below

$$\mu_{TF} = \frac{F_{xF}}{F_{zF}} = \frac{(1-\Phi)aw}{[\left(1-\Psi\right)+a\frac{h}{L}\left.\right)w]} = \frac{(1-\Phi)a}{\left(1-\Psi\right)+a\frac{h}{L}\left.\right)} \qquad (9)$$

Similarly for the rear axle, adhesion demand is calculated as below

$$\mu_{TR} = \frac{F_{xR}}{F_{zR}} = \frac{\Phi aw}{[\left(\Psi-a\frac{h}{L}\right)w]} = \frac{\Phi a}{\left(\Psi-a\frac{h}{L}\right)} \qquad (10)$$

D. *Parking brake calculations*

Air S-cam brakes use compressed mechanical springs as shoe application force for parking brake purposes. The dual chamber consists of the regular service chamber and the chamber containing the compressed spring. When the air pressure holding the spring compressed is lowered or released, the spring expands and applies the shoes against the drum.

The force balance of a vehicle resting on gradient is shown in below figure 2

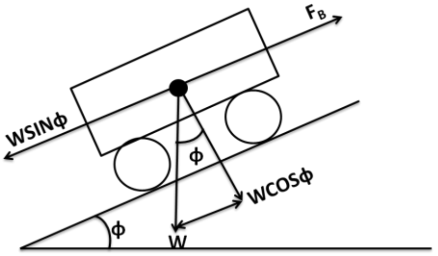


Figure 2. Force Balance on Gradient

The capacity of a parking brake to hold the vehicle stationary is accessed by the maximum gradient (ϕ) a parking brake can hold. It is calculated as below

$$\emptyset = \sin^{-1}\left(\frac{F_B}{W}\right) \qquad (11)$$

Where F_B is a parking brake force & it is given as below

$$F_B = \frac{S_B\ x\ \rho\ x\ BF\ x\ r}{R_R} \qquad (12)$$

Maximum achievable deceleration by parking brake in dynamic condition is calculated as below

$$g' = \frac{S_B\ x\ \rho\ x\ BF\ x\ r}{W x R_R} \qquad (13)$$

III. DEVELOPMENT OF THE PROGRAM

A. *Structure of the Program*

The program consists of three parts. The first part, the pre-processor, feeds data into the program. The feed data consists of vehicle input parameters, foundation brake data & actuation data. The second part, the solver, calculates & analyses all data. Lastly, the post-processor presents the resultant data in the graphical form. The total structure of the program is presented in Figure 3.

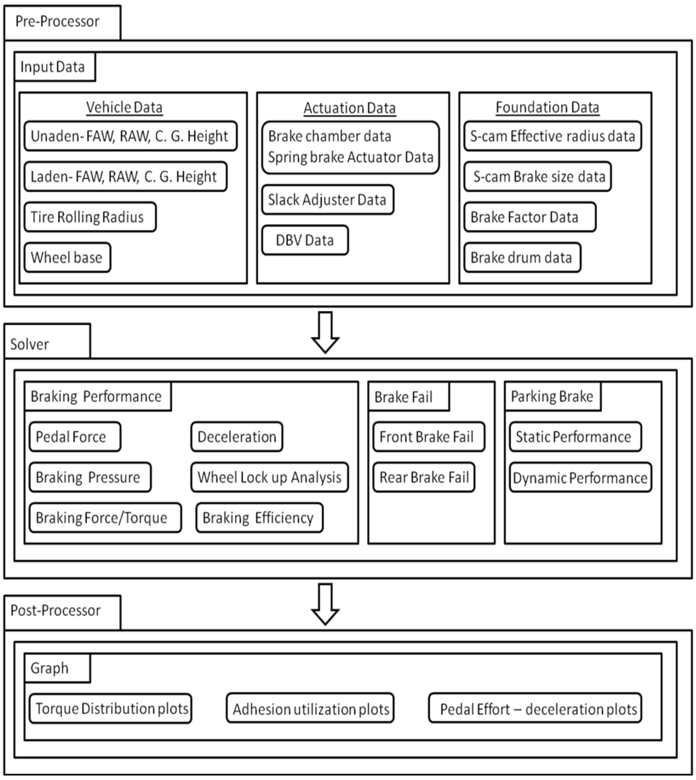


Figure 3. Structure of the program & analyzing process

B. *Pre-Processor*

The input data includes vehicle data such as Front axle weight (FAW) & Rear axle weight (RAW) & Height of center of gravity from ground in vehicle Unladen & laden condition. It also includes foundation data such as S-cam brake size, brake drum size, Brake factor, coefficient of friction of brake linings, S-cam effective radius. The Actuation data includes brake chamber & spring brake actuator size, slack adjuster data, dual brake valve characteristic data. Since all the input files are in MS-EXCEL format, it is very useful to manage the design data & construct a data base.

C. *Solver*

The program computes various braking performances with input data from the pre-processor. The analysis is done according to the deceleration & pedal effort. The calculation results with respect to deceleration include weight distribution, ideal & actual braking force & braking torque distribution, braking pressure, stopping distance & so forth. In this program, deceleration ranges from 0 g to 1.0 g with step of 0.01g. The procedure to obtain actual braking force, actual braking torque, deceleration & adhesion demand with respect to given pedal effort is presented in figure 4

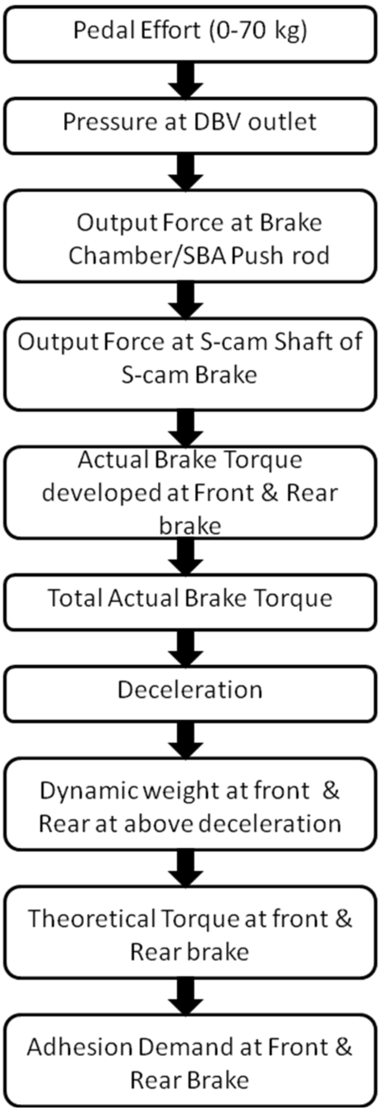


Figure 4. Process to Calculate deceleration & adhesion demand from pedal effort input.

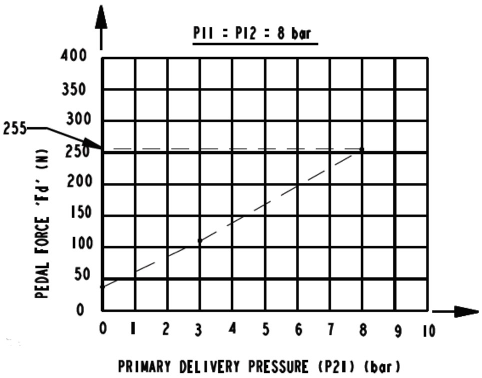
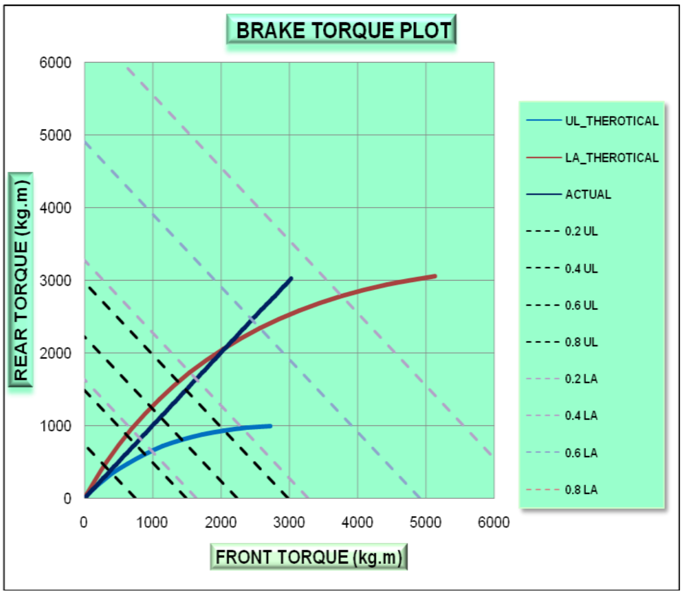


Figure 5. Foot Brake Valve characteristic

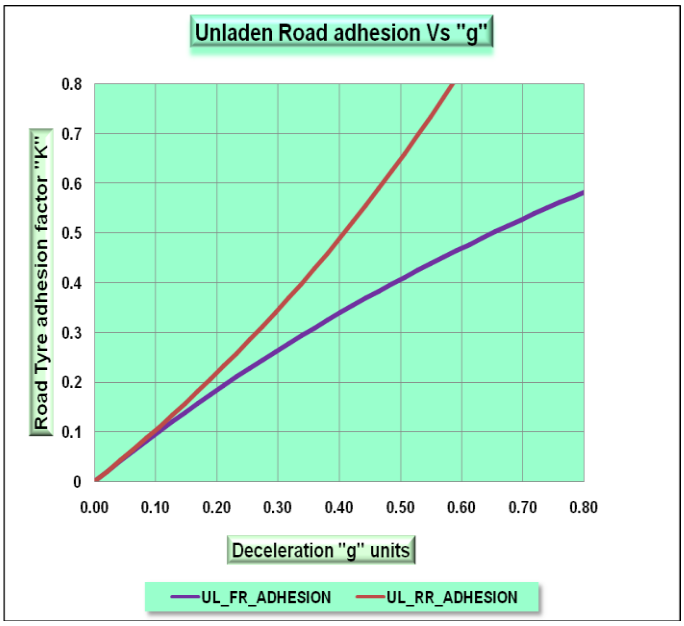
While calculating deceleration & adhesion demand, pedal input & brake line pressure values to be derived from foot brake valve performance characteristic as shown in figure 5

IV. VERIFYING & ANALYSING RESULT DATA

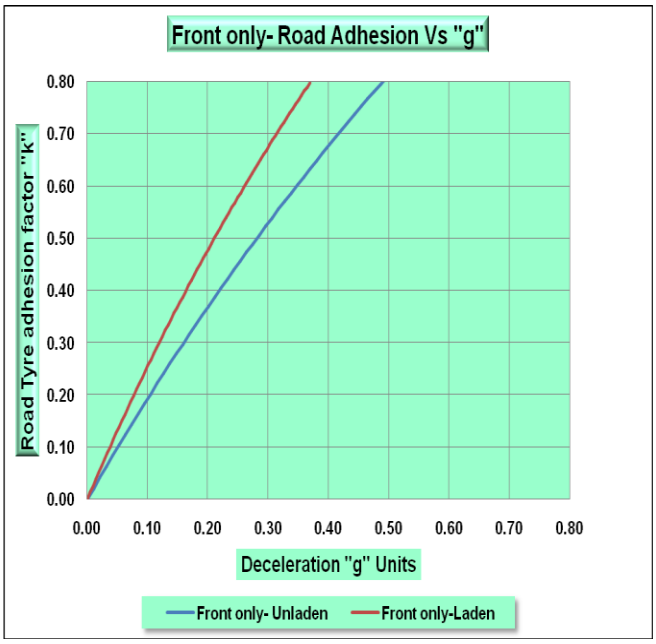
In output of the program, various graphs are drawn like ideal & actual brake torque distribution graph, which shows how close is the actual brake torque to ideal brake torque. Adhesion utilization curves, for front brakes & rear brakes with fully laden & unladen vehicle condition, shows the maximum deceleration to be achieved, just before wheel lock-up. Pedal effort-deceleration graph shows, the maximum pedal effort required to achieve the target deceleration. Above graphs are also drawn for front & rear brake fail conditions separately. Some of the program output graphs are shown below



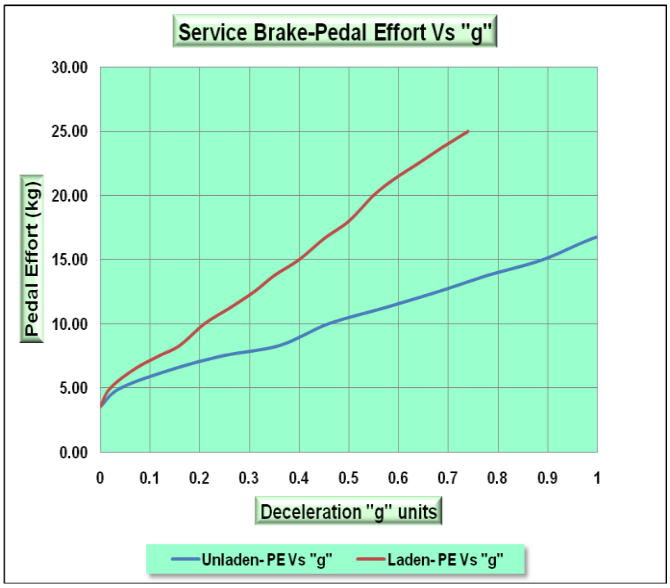
Torque distribution Graph (Ideal & Actual)



Tire adhesion- Deceleration Graph (Unladen)



Tire adhesion- Deceleration Graph (Front brake only)



Pedal Effort- Deceleration Graph

From the output graphs obtained from the program, it can be predicted that whether the brake system configuration selected is capable to meet the regulatory requirements & implied needs of the customer with adequate margin & reasonable accuracy. A fine tuning can be done by selecting appropriate aggregate component sizes from the library products available in design data base.

In table 1, some of the estimated data calculated from the program and the real vehicle test resultant data are compared.

Table 1. Comparision between estimated data and experimental data.

Test condition	Braking characteristics	Regulation	Estimated Value	Experimental Value	% co-relation
Unladen	Deceleration (m/s^2) Minium	5	5.78	5.61	97.06
	Stopping Distance (m) Maximum	36.69	36.09	32.7	90.61
	Pedal Effort (kg) Maximum	70	12	13	92.31
Laden	Deceleration (m/s^2) Minium	5	6.9	5.89	85.36
	Stopping Distance (m) Maximum	36.69	36.09	30.82	85.40
	Pedal Effort (kg) Maximum	70	18	19	94.74

The main source of variation in actual test data & predicted test data is the brake liner behavior at different temperature conditions. Friction coefficient of brake lining material can vary in different temperature conditions. In test procedure of brake lining friction coefficient as per IS 2742, there may be a variation of 10% in brake friction coefficient in normal temperature to high temperature over the range of 80 degree to 350 degree respectively. However the minimum correlation between predicted & actual results is above 85 %. Sufficient margin is always kept in predicted values from regulation to accommodate brake lining performance variations. Therefore the developed program is proven to produce reasonable prediction data of the braking performance of a vehicle to ensure that regulatory requirements are met with sufficient margin.

V. CONCLUSION

In this research, a program for 2-axle vehicle that estimates braking performance of a vehicle equipped with an air brake system was developed & the basis to establish a design data base was presented. Using this program, it is easy to verify elements of braking performance such as brake torque, deceleration, pedal effort & stopping distance. In addition, since the design data of the brake system components & braking characteristics are managed as using MS-EXCEL, each component of the braking system can be inserted into or separated from the whole system independently & designers can verify the changes of braking performance at a glance. With this program users can design a brake system quickly, easily, & efficiently. The program scope can be further widened to incorporate thermal calculations for one stop & ten stop temperatures. Same program can be developed for multi-axle vehicles & also for vehicles having hydraulic brake systems. Finally the brake system could be designed more efficiently if the program could analyze the braking performance of the latest brake system by adding ABS & TCS control logic & utilizing an algorithm that could apply proper braking pressure to the brake actuators & brake chambers after predicting the road-tire friction coefficient.

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VII. NOMENCLATURE

$F_{ZF,dyn}$, $F_{ZR,dyn}$: Front, rear dynamic weight, kg
W: Gross vehicle weight, kg
h: height of C. G. from ground, m
L: Whel base, m
a: Deceleration ratio
F_F, F_R : Ideal braking force, kg
R_R : Dynamic tire rolling radius. m
T_{Fi}, T_{Ri} : Ideal braking torque, kg. m
F_x : Actual braking force, kg
T_a : Actual braking torque, kg.m
ρ : Mechanical gain
P_l : Brake line pressure, bar
P_o : Push out pressure, bar
A_c : Brake chamber area, cm^2
μ_{TF}, μ_{TR} : Adhesion demand for front, rear axle
BF: Brake factor
ϕ : Brake force distribution
S_B : Spring force of spring brake actuator, kg