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Development of a Computer Aided Performance Prediction Model for Hydraulic Brake System

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Abstract: **Innovations in the automobile sector are growing at an alarming pace. Industries are moving through a phase of trusting virtual data similar to actual physical data for implementation. For a vehicle, the brake system is a critical component and its performance is crucial. Design and performance evaluation process existing in industries is a time consuming and costly process. A performance prediction model that could predict the performance of a Non-ABS hydraulic brake system, in terms of stopping distance and MFDD, is elaborated in this paper. The model consists of three sections: Pre-processor, Solver and Post-processor and is coded in MATLAB. Outputs of the model include the performance parameter data and design evaluation data at each checkpoint in the brake system. The model was tested on a commercial vehicle. Physical testing of the vehicle was conducted on NATRAX, Madhya Pradesh, INDIA. On comparison of predicted performance parameters with the physical testing data, co-relation resulted is about 97%. Thus validation of the model proved that it could be used in industries as an alternative to the testing process.**

Keywords: Brake system design, IS standards, Braking performance, Performance prediction model, MATLAB.

INTRODUCTION

Hydraulic brake system is generally incorporated in vehicles with lower tonnage capacity. Passenger vehicle sector uses hydraulic brake system as the design is simplex and its ease of serviceability. Brake system performance should be the prime consideration for passenger safety [1]. Hydraulic Brake system consists of many components such as Pedal, Booster, Regulating valve, Master cylinder and Foundation brakes. Evaluating performance of brake system through physical testing process, in terms of standard performance parameters, requires considerable amount of time, labor and cost. A computerized model which automates the brake system design process and predict its performance in terms of standard parameters could minimize resource utilization.

Suh et al. (2001) developed a package to estimate the braking performance of a tractor-semitrailer vehicle. Choi et al. (2004) examined braking distance with a finite element model of a tire. Hong & Huh (2004) inspected means that approximate braking force & road friction coefficient using a dynamic model of a tire for a particular vehicle. Jung (2007) developed a brake system design program with dynamic considerations in MS Excel. Lee (2009) developed a semi-empirical program for passenger vehicles considering pad compression, hose expansion and friction coefficient between pad and rotor.

Thus on thorough survey it was found that an effective model to predict the performance of a hydraulic brake system hasn't yet been developed. In this paper, a mathematical model that predicts the performance of a Non-ABS hydraulic brake system is elaborated. The model has dynamic considerations including the complex nature of Load Conscious Regulating Valve (LCRV) and vacuum booster. MATLAB software was utilized for coding the model. Validation of the model was conducted on a commercial vehicle, as per Indian Standard: IS 11852. The model provides design values at each checkpoint along with variation of performance parameters like Stopping distance and Mean Fully Developed Deceleration (MFDD). The output data is directly exported in MS Excel format. Output data is represented both numerically and graphically.

1. THEORY AND CONCEPTS

Brakes are designed so as to stop the vehicle running at a particular velocity in limited stopping distance and time. The wheels are restricted from rotational motion when the brake torque produced by the brake foundation is equal to or higher than the torque at the wheels, produced by the running vehicle. Wheel lock phenomenon is occurring when the adhesion demand is crossing the static co-efficient of friction between tire and road [2]. Braking torque and adhesion demand concepts is interpreted in terms of two models, i.e. Deceleration model and Pedal Effort model.

1.1 Deceleration model

The force exerted by each wheel of a vehicle on the ground may or may not be different. Thus the brake force required to stop each wheel is also different. This model relates to the procedure to calculate the brake torque required to stop the vehicle from motion. In the quest to find out the brake torque required at each wheel end, both static and dynamic condition at laden as well as unladen status is considered. In dynamic condition, the effect of weight transfer from rear to front axle is considered.

Ratio, χ = Height of Center of Gravity (C.G) from ground (h) / Wheelbase (x) = h / x

Weight transfer, Wtrans = GVW * χ * a

Thus,

(FAWdyn) = FAW + Wtrans

(RAWdyn) = RAW - Wtrans

ϕ = (RAWdyn)/ {(FAWdyn) + (RAWdyn)}

Therefore,

$(T_{br})_{dyn}$ = RAWdyn * μ * R

$(T_{bf})_{dyn}$ = FAWdyn * μ * R

Thus by the above procedure, brake torque required to stop the wheels at both axles could be determined. The adhesion co-efficient of roads vary with the material of road, temperature, velocity etc. the tire rolling radius also.

1.2 Pedal effort model

This model intends to determine the brake torque at wheels produced at various pedal efforts. Model includes the calculations and considerations of each component in the brake system. It includes both mechanical as well as the hydraulic components. This model starts addressing the brake torque from the pedal effort till the brake caliper.Frictional force at the Front, F_F = Force at two sides of the brake disc at Front * μ_{BR}
Frictional force at the Rear, F_R = Force at two sides of the brake disc at Rear * μ_{BR}
Front wheel Brake Torque, T_{BF} = F_F * Effective brake radius as R_{BR}
Rear wheel Brake Torque, T_{BR} = F_R * Effective brake radius as R_{BR}

1.3 Braking Traction Coefficient

The wheel brake torques produce braking between the tire and the ground. The ratio of braking force to dynamic axle load is defined as the traction coefficient μ_{Ti}:

$\mu_{Ti} = F_{xi} / F_{zi,dyn}$

The traction coefficient varies as either braking force or dynamic axle load change. It is also a vehicle deceleration dependent parameter. The traction coefficient must not be confused with the tire-road coefficient of friction. The wheels stops when the traction co-efficient is higher that the tire-road coefficient of friction.

2. BRAKE STANDARD SPECIFICATIONS

Brake performance of a vehicle is judged according to IS 11852 standard in India. It specifies that the vehicle should either qualify the stopping distance or MFDD criteria.

- Stopping distance

The distance covered by the vehicle from the moment when the driver begins to trigger the control of device until the moment vehicle stops [3].

- Mean Fully Developed Deceleration (MFDD)

Mean value of deceleration over the period of the fully developed deceleration between the instant when deceleration reaches its stabilized value and the instant when vehicle stops [3].
Table 1 shows the stopping distance and MFDD criteria for various categories of vehicles

Table 1 Brake performance criteria

Category	Engine disconnected			Engine connected		
	V (km ph)	S (m) Max	d_m (m/s²) min	V (km ph)	S (m) Max	d_m (m/s²) min
M1	80	≤ 0.1V + V^2/150	5.8	160	< 0.15V + V^2/130	5.0
M2	60			100		
M3	60			90		
N1	80	≤ 0.15V + V^2/130	5.0	120	< 0.15V + V^2/130.5	4.0
N2	60			100		
N3	60			90		

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3. STRUCTURE OF PERFORMANCE PREDICTION MODEL

The model consists of three sections as shown in Table 2-4. Process flow in the model is as shown in Figure 1. The model has been coded in MATLAB software. First section is the Pre-processor which takes inputs from the user. All the required inputs of the vehicle as well as the brake system, to be tested, is inputted in to the model. Model takes 20 input parameters which could be categorized into vehicle data, transmission data and foundation data.

Second section of the model is the solver. This section is the processing section of the model. Solver section takes the inputs from the pre-processor and provides the outputs to the post-processor. Performance parameters and the design evaluation is processed in this section. The comparison of predicted and standard data is also performed in this section.
Third section of the model is the Post-processor. In this section all the outputs are evaluated and stored, both in numerical as well as graphical form. Outputs include the performance parameter data and the design data at each checkpoints. The output data shows the variation of design parameters at each checkpoint of the brake system.

Table 2 Preprocessor section of model

Pre-processor (Input data)		
Vehicle data	**Transmission data**	**Foundation data**
Unladen FAW, RAW,GVW	Pedal data	Front caliper data
Unladen C.G height	Booster data	Rear caliper data
Laden FAW, RAW,GVW	TMC data	Front rotor data
Laden C.G height	LCRV data	Rear rotor data
Tire rolling radius		Pad data
Wheel base		
Adhesion Co-efficient		

Table 3 Solver section of model

Solver (Processor)	
Braking performance	**Brake condition**
Pedal force	Front wheel
Booster force	Rear wheel
Front line pressure	Traction co-efficient
Rear line pressure after LCRV	Dynamic performance
Caliper braking force	
Total braking force	
Braking torque generated	
Braking torque required	
Hydraulic gain	
Braking efficiency	

Table 4 Post-processor section of model

Post-processor (Output data)	
Performance	**Graphs**
Deceleration data	Front vs. Rear Torque
Stopping distance data	LCRV characteristics
	Before and After LCRV
	Pedal effort vs. Pressure
	Pedal effort vs. Deceleration

Validation of the model was conducted by testing the model on a commercial vehicle. Model was used to predict the performance of the brake system inbuilt in the vehicle. After obtaining the predicted results, the vehicle was tested physically on the standard brake performance determination track at NATRAX, Madhya Pradesh, India. Testing was conducted for all the conditions like Full-healthy, Rear only, Front only and Booster fail for both Laden and Unladen conditions. The validation procedure for the model compares the predicted data with the physical testing data for both the performance parameters as well as the design data at each checkpoints.

4. RESULTS AND DISCUSSION

The results were obtained directly in excel format for all the required forces, pressures, torques and the performance parameters. Excel format was chosen for its simplicity in usage. The predicted data obtained was compared with the physical testing data of vehicle. The co-relation is as shown in Table 5. The correlation obtained is about 97%, i.e. the predicted data is accurate and within the limits that is acceptable according to industry standards.

The output from model also include the graphs which shows the variation of parameters like line pressure, deceleration and torque at each axle with pedal effort. Outputs is as shown in Figure 2-6. Figure 2 shows the variation of rear axle torque w.r.t front axle torque. The variations in Unladen, Laden and the generated torque condition is shown.

Figure 3 shows the variation of deceleration of the vehicle w.r.t pedal effort. The variation is shown for both unladen and laden condition. The linear deviation shown in the graph is due to the effect of LCRV.

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Table 5 Correlation data

Particulars / Performance Parameters	Specification	Test data	Predicted data	Correlation
MFDD (m/s^2)	≥ 5.0	5.8	5.62	96.89
Stopping Distance (m)	≤ 36.7	28.2	27.34	96.95

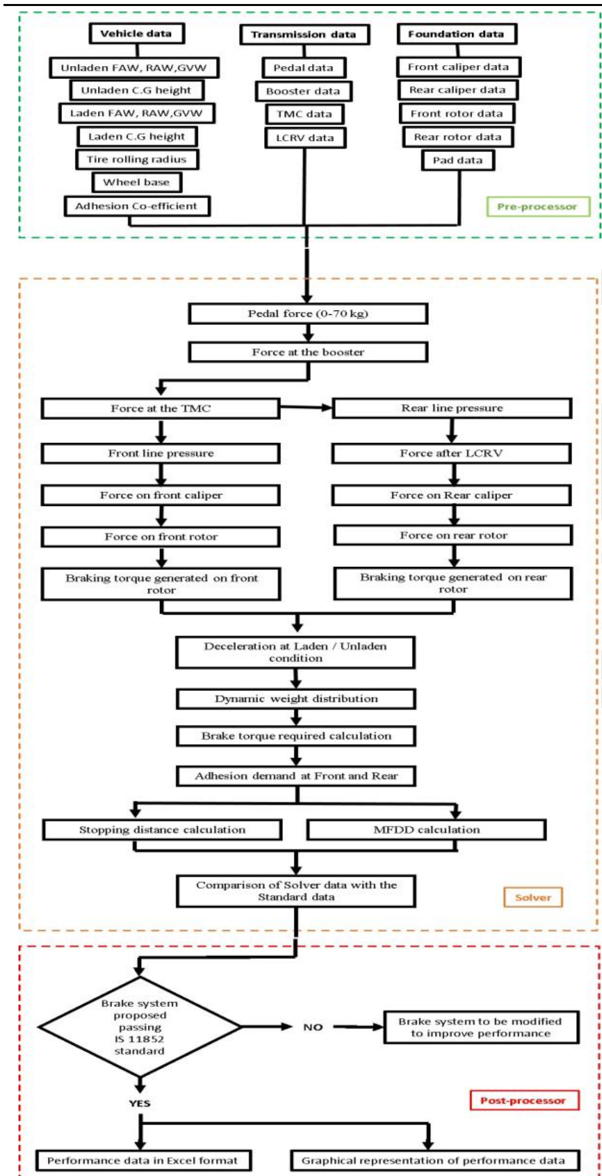

Figure 1 Process flow in the prediction model

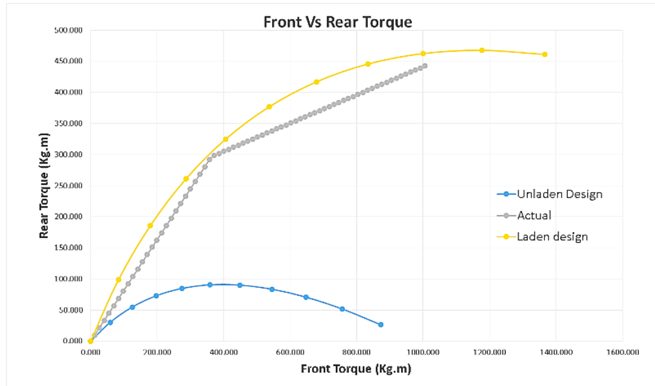

Figure 2 Front vs. Rear torque

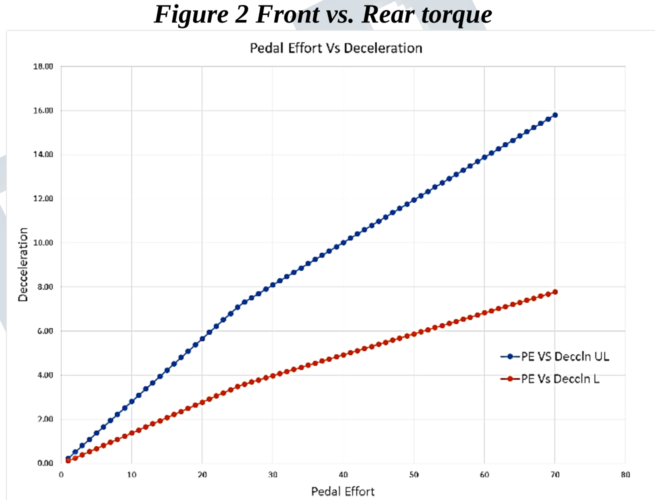

Figure 3 Pedal effort vs. Deceleration

Figure 4 shows the variation of line pressure before and after LCRV. The variation is shown for both Unladen predicted data and for Unladen test data. The correlation of the data could be understood from the graph. The deviation is taking place after the LCRV cut-in pressure. The means the design or the setting of the LCRV component is incorrect.

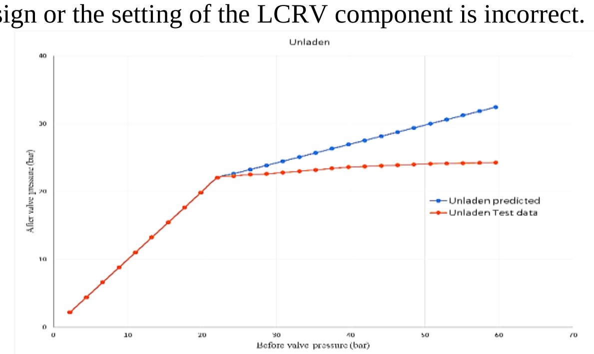

Figure 4 Unladen line pressure before and after LCRV

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Figure 5 shows the variation of line pressure before and after LCRV. The variation is shown for both Laden predicted data and for Laden test data. The correlation of the data could be understood from the graph. The deviation is taking place after the LCRV cut-in pressure. The means the design or the setting of the LCRV component is incorrect.
Figure 6 shows the booster characteristics. It shows the variation of line pressure with the pedal effort. The curves are shown for conditions like: with booster test data, with booster predicted data, without booster test data and without booster predicted data. The correlation between the test data and the predicted data in both with booster condition as well as without booster condition is 100% so it's impossible to differentiate between these curves.

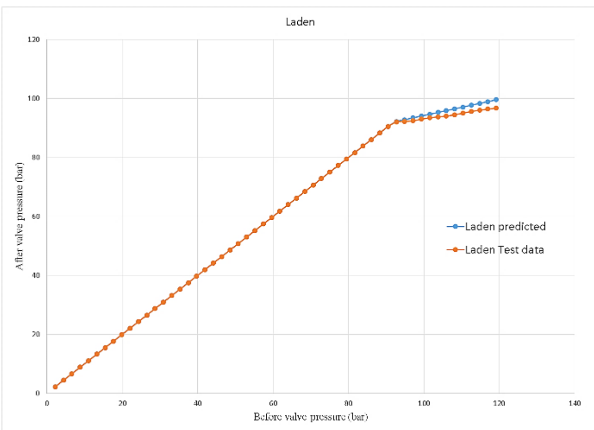

Figure 5 Laden line pressure before and after LCRV

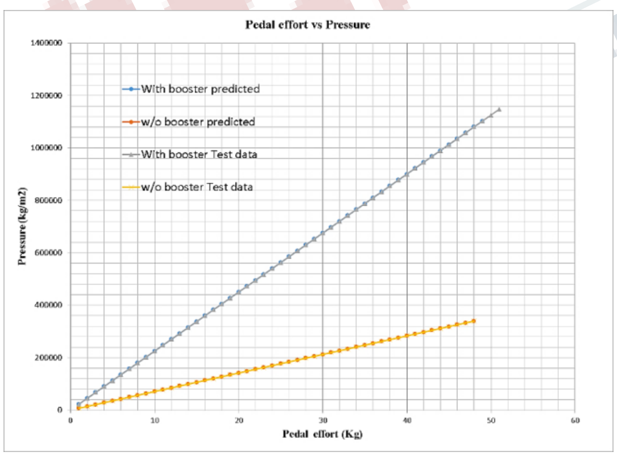

Figure 6 Booster characteristics

Figure 7-9 are variations obtained to understand the deviation of deceleration w.r.t Brake Effective Radius (BER), Tandem Master Cylinder diameter and Caliper piston diameter. Figure 7 shows the variation of vehicle deceleration with varying brake effective radius. Deceleration is showing a positive linear variation with increasing BER.

Figure 8 shows the variation of vehicle Deceleration with varying TMC diameter. Deceleration is showing a negative non-linear deviation w.r.t the increasing TMC diameter. This variation is due the reduction in hydraulic gain in the brake system.

Figure 9 shows the variation of vehicle Deceleration with varying Caliper piston diameter. Deceleration is showing a positive linear deviation w.r.t the increasing Caliper piston diameter. This variation is due the increase in hydraulic gain in the brake system.

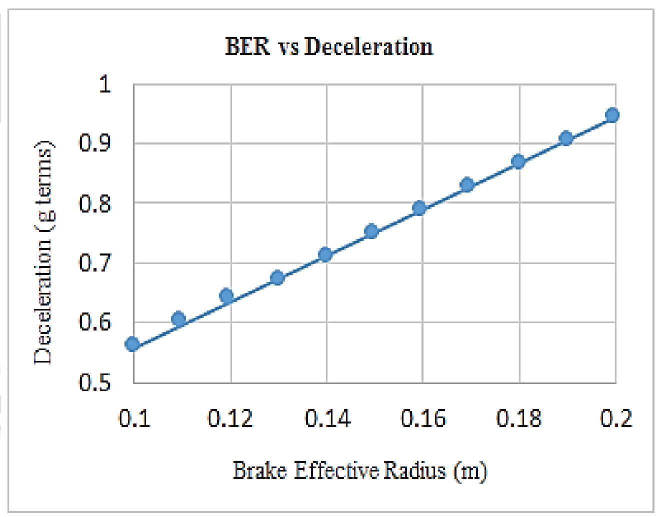

Figure 7 BER vs. Deceleration

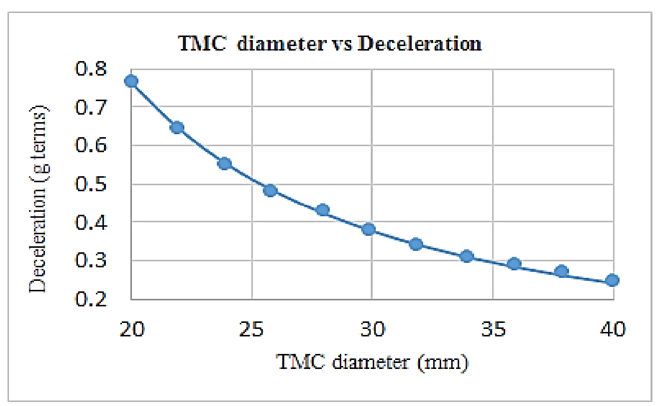

Figure 8 TMC diameter vs. Deceleration

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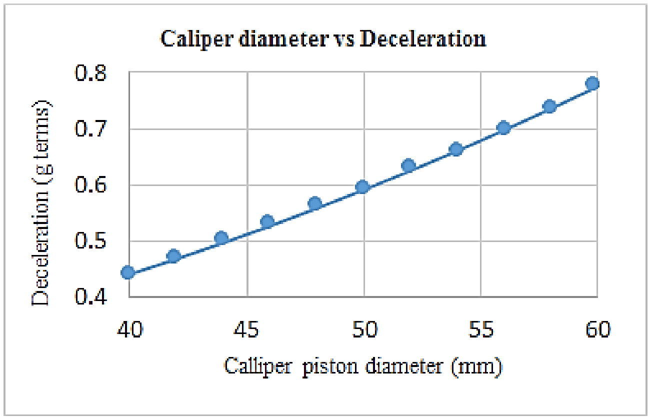

Figure 9 Caliper diameter vs. Deceleration

The results were examined in order to refine the model. The inconsistency and errors are arising due to the inability to maintain design ratios in the production line. Components like LCRV and booster will serve its designed purpose only if the ratios and connections are provided on the vehicle as per the design specifications. The errors could also arise due the inaccurate selection of system components. The above mentioned errors could be minimized but not eliminated. Thus the error of the performance prediction model is rated at about three percent, which is within the acceptable limit.

5. CONCLUSION

Vehicle performance is highly influenced by the inbuilt brake system's performance. Existing performance determination of a particular brake system on a vehicle is a highly resource consuming process. Thus a programmed model that could accurately predict the performance parameters at each condition could minimize the resource utilization. Performance prediction model for a Non-ABS Hydraulic brake system is explained in this paper. The model has been coded in MATLAB. Vehicle used for correlation purpose was a commercial vehicle. Physical testing of the vehicle was conducted on national approved test track. The results were analyzed and a co-relation of about 97% was obtained with the model. The model could be resourceful to industries in predicting the brake system performance of a particular vehicle even before physical testing.

6. REFERENCES

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ABBBREVATIONS

MFDD	Mean Fully Developed Deceleration
ABS	Anti-lock Braking System
NATRAX	National Automotive Test Tracks
MS Excel	Microsoft Excel
MATLAB	Matrix Laboratory
LCRV	Load Conscious Regulating Valve
TMC	Tandem Master Cylinder

BER	Brake Effective Radius
IS	Indian Standard
C G	Center of Gravity
GVW	Gross Vehicle Weight
FAW	Front Axle Weight
RAW	Rear Axle Weight
FAWdyn	Dynamic Front Axle Weight
RAWdyn	Dynamic Rear Axle Weight
Wtrans	Weight Transfer
(Tbr)dyn	Dynamic Torque of rear axle
(Tbf)dyn	Dynamic Torque of front axle

SYMBOLS

a	Deceleration
ϕ	Brake force distribution
μ	Co-efficient of friction
R	Brake effective radius
F_{xi}	Braking force generated
$F_{zi,dyn}$	Dynamic force on the axle
d_m	Mean Fully Developed Deceleration

