Brake Optimization Technique using Simulink

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Abstract - *The design lead time required to calculate the accurate stopping distance of a vehicle is optimized and the same is physically measured and verified. The calculation of vehicle's accurate stopping distance is modelled using Simulink and the driver behavior is kept constant for reducing complication. The calculated stopping distance of a vehicle using Simulink model is verified physically using a decelerometer and the stopping distance is measured in test run. This new calculation technique using the Simulink model helps in optimizing and reducing the lead time during IC Engine to EV Conversion projects. The efficiency of the vehicle's braking system is maintained same, even after the powertrain system is completely changed.*

Key Words: **Stopping Distance, Simulink, Leverage, Deceleration, Calliper, Decelerometer, Objective.**

1. INTRODUCTION

The brakes are one of the most important control components of vehicle. They are required to stop the vehicle within the smallest possible distance and this is done by converting the kinetic energy of the vehicle into heat energy which is dissipated into the atmosphere.

A Simulink model of braking system is designed with theoretical calculations and formulas. A small control logic is developed in order to get the exact stopping distance and stopping time. A vehicle is selected for this practical experimentation of braking and the input parameter of this vehicle is considered as the input for the Simulink model, same vehicle is calculated after converting it from IC Engine into EV. Using the decelerometer, the results of practical braking experiment on the IC vehicle is derived. The decelerometer works on the principle of piezoelectric effect. The device has to be placed on a flat surface of the vehicle. When the vehicle starts to decelerate this device activates and starts to record the values, some tolerance for deceleration is pre-programed in the device so that it neglects small deceleration of the vehicle during gear shifts. This device gives peak and average value of front-back deceleration in terms of percentage g units, peak and vehicle pull of left-right acceleration in terms of percentage g units and left-right direction, the speed at which the vehicle started to decelerate in kilometre per hour, stopping distance in meter and peak brake efficiency in percentage.

Before introducing any final component in an automotive system it has to undergo two stages of evaluation, first the objective validation and next the practical validation. In objective analysis a theoretical calculation is validated using any tool like Simulink model and in Practical analysis, practical experimentation is done to derive the values and to determine the percentage difference between Practical and objective analysis.

1.1 Design Finalization Procedure

Before finalizing any component in Brake System it has to undergo the following steps:

Step.1 – Benchmarking

Step.2 – Design Size Finalization

Step.3 – Virtual Validation using Computer Aided Tool

Step.4 – Practical Testing

Design Lead Time is based on the above four steps. In order to reduce time in Step 2, 3, 4 Dynamic Mathematical Model for Brakes is developed in Simulink which will reduce the loop time in Brake Sizing Finalization and it is practically tested using a Decelerometer. Following simulations are made in such a way that IC Engine is converted into EV with holding the same brake parts.

2. Dynamic Brake Simulink Model

2.1 Brake Pedal

All dimensions are in S.I units.

Pedal leverage ratio = L_2 / L_1

$F_{bp} = F_d \times (L_2/L_1)$

The pedal force is directly proportional to deceleration

Where,

F_{bp} = Force output of the assembly

F_d = Human pedal force

L_1 = Distance from the brake pedal arm pivot to the output rod clevis attachment

L_2 = Distance from the brake pedal arm pivot to the brake pedal pad

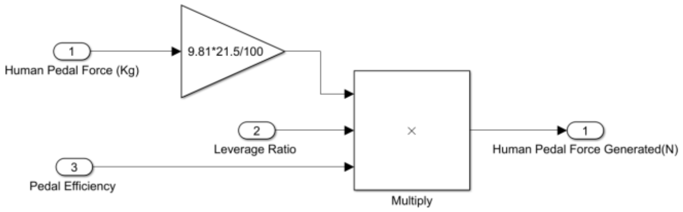

Fig-1: Brake Pedal Block

2.2 Brake Master Cylinder

$A_{ms} = (\pi/4) \times D_{mc}^2$

$P_{mc} = F_{bp} / A_{mc}$

Where,

P_{mc} = hydraulic pressure generated by the master cylinder

A_{mc} = effective area of the master cylinder hydraulic piston

D_{mc} = Diameter of master cylinder piston.

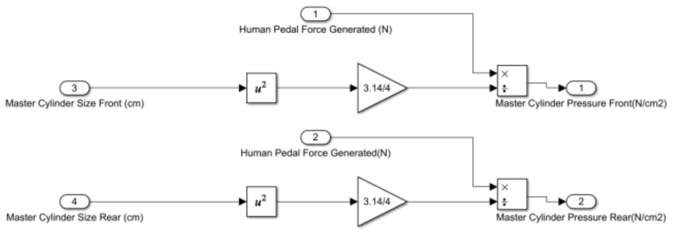

Fig-2: Brake Master Cylinder Block

2.3 Brake Caliper

$A_{cal} = (\pi/4) \times D_{cal}^2$

$P_{cal} = P_{mc}$

Where,

Acal = the effective area of the caliper piston

P_{cal} = Pressure transmitted to caliper

D_{cal} = Diameter of caliper piston

One sided linear mechanical force generated by the caliper will be equal to

$F_{cal} = P_{cal} \times A_{cal}$

The clamping force will be equal to twice the linear mechanical force as follows

$F_{clamp} = 2 \times F_{cal}$

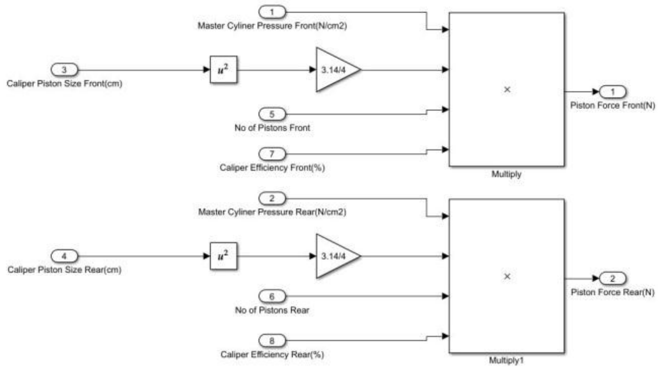

Fig-3: Brake Caliper Block

2.4 Brake Pad

The frictional force is related to the caliper clamp force as follows

$F_{friction} = F_{clamp} \times \mu_{bp}$

Where,

μ_{bp} = the coefficient of friction between the brake pad and the rotor.

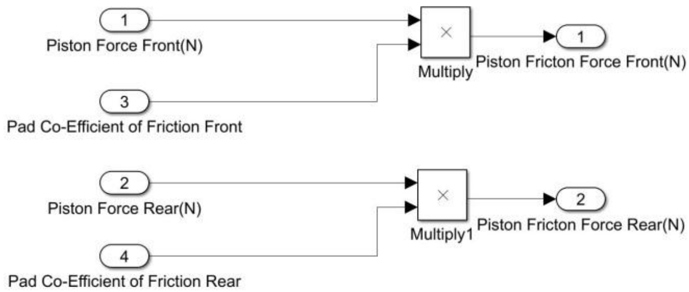

Fig-4: Brake Pad Block

2.5 Brake Rotor

The torque is related to the brake pad frictional force as follows

$T_r = F_{friction} \times R_{eff}$

Where,

T_r = torque generated by the rotor

R_{eff} = the effective radius of the rotor (measured from the rotor center of rotation to the center of pressure of the caliper pistons)

As the rotor is mechanically coupled to the hub and wheel assembly and the tire is assumed to be rigidly attached to the wheel, the torque will be constant throughout the entire rotating assembly as follows

Torque on Tire (T_t) = Torque on wheel (T_w) = Torque on rotor (T_r)

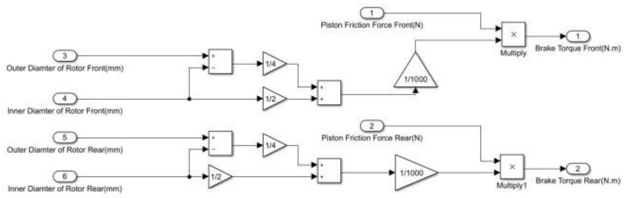

Fig-5: Brake Rotor Block

2.6 Tire

The force reacted at the ground will be equal to

Force on the front tire = $F_{front} = T_t / R_{front}$

Where,

R_{front} = effective rolling radius of front tire

Force on the rear tire = $F_{rear} = T_t / R_{rear}$

Where,

R_{rear} = effective rolling radius of rear tire

The total braking force reacted between the vehicle and the ground

$F_{total} = (2 \times F_{front}) + (F_{rear})$

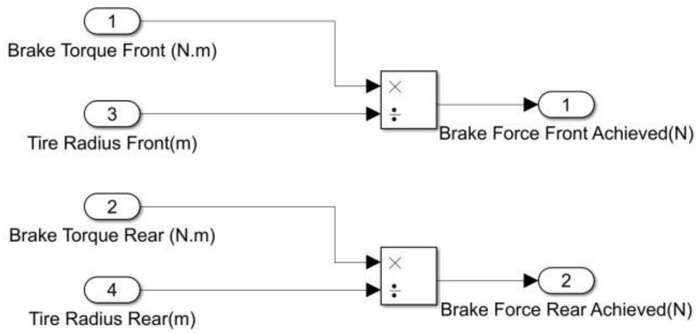

Fig-6: Tire Block

2.7 Deceleration

The deceleration of the vehicle will be equal to

$a_v = F_{total} / m_v$

Where,

a_v = deceleration of vehicle

m_v = mass of vehicle

2.8 Stopping Distance

Simulation is carried out in such a way like vehicle is traveling at a constant test speed and brakes are applied. In order to avoid wheel locking a control logic is developed.

$a_v = -dV/dt$

Integrating this equation from initial velocity V_0 to final velocity V_f

$$\int_{v_0}^{v_f} dV = -\frac{F_{total}}{m_v} \int_{0}^{t_s} dt$$

$V_0 - V_f = (F_{total} / m_v)\, t_s$

Since, V = dx/dt, substituting and integrating,

$$\frac{v_0^2 - v_f^2}{2} = \frac{F_{total}}{m_v} X$$

If deceleration is full stop then $V_f = 0$ and X is the stopping distance.

The theoretical stopping distance of a vehicle in motion can be calculated as follows

$d = v^2 / 2a_v$

Where,

v = velocity of vehicle

d = stopping distance

2.9 Stopping Time

The theoretical braking time of a vehicle in motion can be calculated as follows

$T_{stop} = (v \times m_v) / F_{total} = v / a_v$

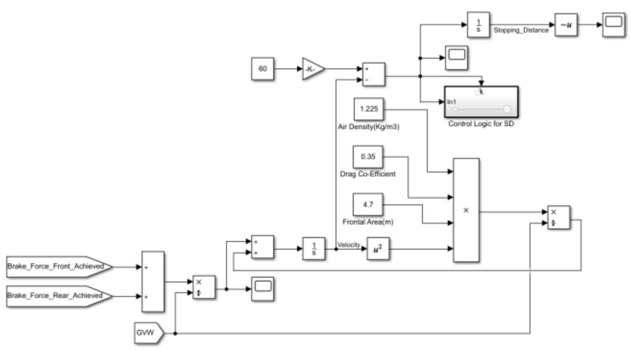

Fig-7: Deceleration Block

2.10 Load Transfer

From the vehicle's center of gravity,

$V_f = (V_t \times CG_r) / WB$

Where,

V_f = front axle vertical force

CG_r = distance from the rear axle to the CG

WB = wheel base (distance from the front axle to the rear axle)

V_t = Total vertical force of vehicle

$V_r = (V_t \times CG_f) / WB$

Where,

V_r = rear axle vertical force

CG_f = distance from the front axle to the CG

Percentage front weight = $(V_f / V_t) \times 100$

Percentage rear weight = $(V_r / V_t) \times 100$

Load transfer from the rear axle to front axle,

$WT = (a_v/g) \times (h_{cg}/WB) \times V_t$

Where,

g = acceleration due to gravity

h_{cg} = height of CG from the ground

In order to calculate the steady-state vehicle axle vertical forces during a given stopping event, the weight transferred must be added to the front axle static weight and subtracted from the rear axle static weight as follows:

$V_{fd} = V_f + WT$

$V_{rd} = V_r - WT$

Where,

V_{fd} = the front axle dynamic vertical force for a given deceleration

V_{rd} = the rear axle dynamic vertical force for a given deceleration

The maximum braking force that an axle is capable of producing is defined by the following relationships

$F_{tires,fd} = \mu_f \times V_f$

$F_{tires,rd} = \mu_r \times V_r$

Where,

$F_{tires,fd}$ = the dynamic force on front tire

μ_f = coefficient of friction between front tire and road

$F_{tires,rd}$ = the dynamic force on rear tire

μ_r = coefficient of friction between rear tire and road

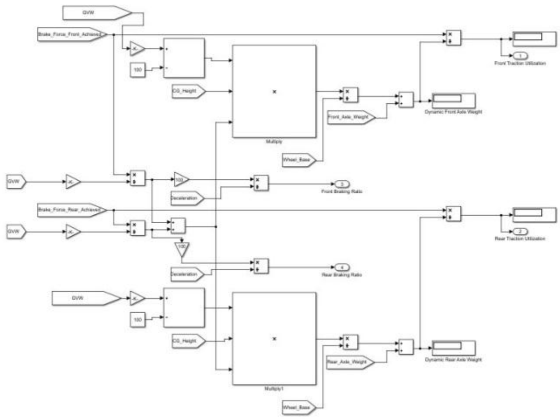

Fig-8: Load Transfer Block

3. Input Parameters

Table-1: Input parameters for Simulink model

Input	Units	Values
Leverage ratio		5
Tandem master cylinder	mm	19.05
Caliper piston size	cm	4.2
Disc diameter	mm	256
Disc thickness	mm	22
Velocity	kmph	60
GVW	kg	1570
Front Axle Weight	kg	800
Rear Axle Weight	kg	770
Wheel Base	mm	2469
Tire specification	-	175/70 R14
Coefficient of Friction between Pad and Disc	-	0.4
Coefficient of Friction between Road and Tire	-	0.7

These parameters are used as inputs in Simulink model. These input parameters are the values of selected vehicle for testing. From the tire specification data the effective radius of tire is calculated. After running the program the results from Simulink model is tabulated below including the graph it generated.

4. Results

Table-2: Results from Simulink model

Simulink Result		
Time	Distance-IC	Distance-EV
0	0	0
0.5	-7.8	-8.2
1	-16.5	-16.1
1.5	-22.9	-23.2
2	-28.3	-29.2
2.5	-31.3	-33.5
2.8	-32	-35
3	-	-35.8
3.2	-	-36

4.1 Stopping Distance Curve

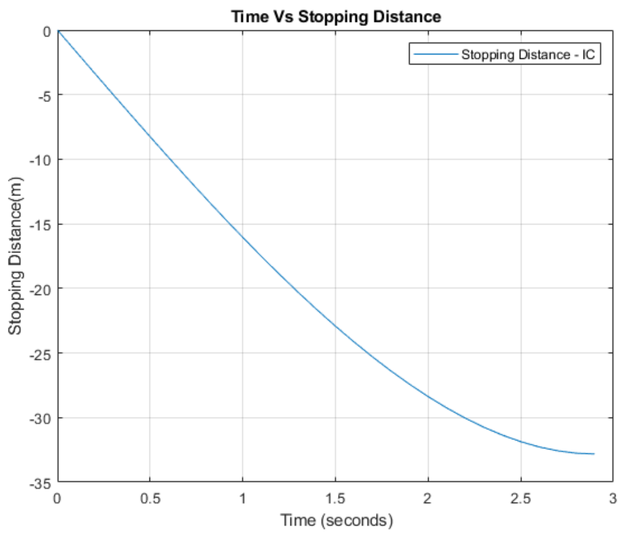

Fig-9: IC Vehicle Time Vs SD Graph

In the above graph, IC vehicle is accelerated for test speed and then the brakes are applied and following stopping distance is achieved.

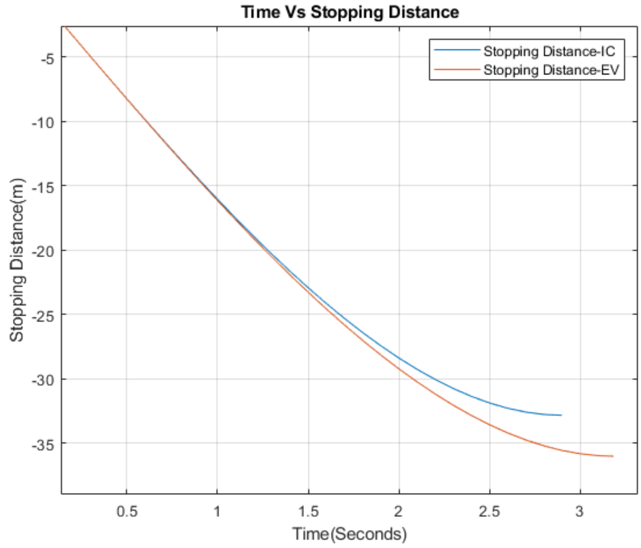

Fig-10: Comparison of IC & EV

In the above graph it can be clearly seen that Stopping Distance in EV exceeds IC vehicles and it takes more time to bring for the vehicle to halt. So by keeping the brake parts constant and swapping from IC to EV will create a serious issue in achieving Standards for Stopping Distance. It is very much prone for Wheel Locking.

5. Practical Analysis using Decelerometer

This 3-Axis Accelerometer measures peak deceleration Front/Rear, measures average deceleration Front/Rear, measures peak acceleration Left/Right and vehicle pulls Left/Right indication and value. It also calculates Brake Efficiency, calculates Stopping Distance, calculates test Speed and also can be used for hand brake test. This also measures ambient temperature in °C and °F.

This device determines braking efficiency of both the Service Brake (Foot Brake) and Hand Brake by measuring the rate of deceleration from a speed of around 20 mph until the vehicle comes to rest. Designed to be self-compensating, the instrument will indicate on the LED screen when it is positioned level enough to perform a brake test, with a generous tolerance to ensure that this is easy to achieve.

The unit indicates whether the vehicle pulls to the left or right during braking.

Test results can be viewed on the display panel or downloaded to a PC for saving or printing. A printed report can also be produced at the time of testing using the portable infra-red printer. The device operates on a rechargeable lithium-ion battery pack.

5.1 Test Description

The 3-Axis Accelerometer device has to be placed on a flat surface of the vehicle. When the vehicle starts to decelerate this device activates and starts to record the values, minor tolerance for deceleration is pre-programed in the device so that it neglects small deceleration of the vehicle during gear shifts. 3-Axis Accelerometer gives peak and average value of front-back deceleration in terms of percentage g units, peak and vehicle pull of left-right acceleration in terms of percentage g units and left-right direction, the speed at which the vehicle started to decelerate in kilometre per hour, stopping distance in meter and peak brake efficiency in percentage.

5.2 Results from Decelerometer

Table-3: Results from Decelerometer

Test Description	Service Brake Test		
Vehicle Model	Units	Test 1	Test 2
Front-Back Deceleration			
Peak	g	0.48	0.5
Average	g	0.34	0.4
Left-Right Deceleration			
Peak	g	0.07	0.06
Vehicle Pulls	L/R	R	L
Test Speed	km/h	60	60
Stopping Distance	m	37	35
Brake Efficiency	%	57	61

The above tabulated values are the results from decelerometer while conducting two tests on the selected vehicle.

5.3 Comparison of values from Simulink model and Decelerometer

Percentage difference= (exact-approx)/exact

% error = [(0.51-0.49)/0.51]x100 = 3.9%

5.4 Summary/Conclusion

By comparing both the practically measured values using decelerometer and theoretically calculated results from Simulink model, almost both are similar but with minute variations which are negligible and hence this can be validated. It is clearly understood that while converting IC to EV with same brake parts will lead to under design of brake parts and increase design lead time. By using this method (Simulink Model) it is possible to reduce the design lead time with results closer to practical values during IC to EV conversion.

5.5 Future Development

There is a slight variation between practical and objective validation which is negligible but still the further development scope in this field is adding filters in the Simulink model to further reduce the variation.

6. References

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