Design and Validation of Hydraulic brake system for Utility Vehicle

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ABSTRACT

The brake system is one of the most important features on all the road vehicles. It must meet manufacturers and Customer requirements in addition to safety standards. This work will analyse automotive braking from vehicle system perspective, emphasizing on legal requirements as well as performance expectations such as Brake pedal effort, Stopping distance and decelerations. The theoretical calculations along with the legal requirements will be verified through the vehicle level validation.

Keywords — Deceleration, Brake balancing, Adhesion curve

I. INTRODUCTION

The highest goal of a good brake system design must be that the vehicle when braking obtains a short braking distance and it does not leave its track and remains steerable. For the solution of this problem, one must consider the dynamics of the braking process. The layout of the braking forces at the front and rear axles for the optimization of the vehicle deceleration. These are essential for different vehicle configurations and loading conditions. The so-called braking dynamics ask first for the optimization of the vehicle deceleration but does not ignore aspects of the braking stability. A vehicle is regarded as stable while braking if its brake system design prevents unwanted vehicle movements automatically, which are either caused by (wrong) actions of the driver or by disturbances of any kind.

In this paper the stability of the vehicle can be achieved through system sizing calculations and the verification is done through vehicle testing.

II. DESIGN OBJECTIVE

The following are the Design objectives, which need to be achieved both in Design calculation as well as in the vehicle validation

1. The brake pedal effort need to be within 50kg under all conditions
2. The designed vehicle has to meet the safety regulations as per IS: 11852 part:3
3. The front wheel has to lock much before Rear wheel; this is achieved by brake balancing.
4. Co-relation between the theoretical and vehicle testing data with the following:
   A. Unladen front V/s Rear pressure
   B. Laden front v/s Rear pressure
   C. Unladen pedal travel v/s Deceleration
   D. Laden pedal travel v/s Deceleration

III. PROPOSED METHODOLOGY

A. Brake system design considerations
In most cases the brake engineer has the following data available when designing the brakes of a vehicle
Empty and loaded vehicle weight
Static weight distribution lightly and fully laden
Wheelbase
Center of gravity height lightly and fully laden
Intended vehicle function
Tire and Rim size
Maximum speed
Braking standard
In the fourth step, the pedal assembly and power boost system is designed.
In the fifth step, the brake system components must be packagable in the vehicle layout.

B. Flow chart for Brake system Design

[Diagram of flow chart]

Step 1: Vehicle Data
Step 2: Size Front Brakes
Step 3: Size Rear Brakes
Step 4: Packaging
Step 5: Brake Balancing
Step 6: Confirm Thermal attributes
Step 7: Master Cylinder sizing
Step 8: Booster sizing
Step 9: Legal requirement, Customer specification
Step 10: Design constraints met?
Step 11: Vehicle Testing

As per Fig 1, the following basic data need to be obtained:

a. FAW = Front axle weight
b. RAW = Rear axle weight
c. H = Center of gravity (C.G)
d. W.B = Wheelbase

Step 2: Size Front Brakes

The following inputs are required:

a. Caliper piston diameter
b. Effective radius
c. Pad Mue
d. Application pressure

Step 3: Size Rear Brakes

The following inputs are required:

a. Brake drum diameter
b. Wheel cylinder
c. Brake factor
d. Application pressure

Step 4: Packaging

The below figures 2, 3 and 4 depicts the brake system packaging

C. Step by step procedure for the Brake system design

Step 1: Vehicle Data
Step 5 and 6: Brake balancing
To calculate the front & rear brake contribution, the following are the formulas
1. Weight @ front = FAW + (m*(C.G/W.B))*Deceleration
2. Weight @ Rear = RAW - (m*(C.G/W.B))*Deceleration
3. Brake force @ front = Deceleration* Weight @ front
4. Brake force @ Rear = Deceleration* Weight @ Rear
5. Ideal torque (kg.m) = Brake force @ front or rear * Dynamic rolling radius
6. Total drag force = m* Deceleration
7. Total Torque = Ideal torque @ front + Ideal torque @ Rear
8. Total Torque = Tfront + Trear
   = 2^2*Awc^2μ*(P-Po)*reff + 2*Awc*B.F *(P-Po)* Reff
9. Percentage contribution of brake for the Front = [(Front Torque/Total Torque)*100]
10. Percentage contribution of brake for the Rear = [(Rear Torque/Total Torque)*100]

Step 6: Thermal attributes
The brakes convert kinetic energy into heat. To determine the energy absorbed, it is to calculate the change in kinetic energy of the vehicle. The change in energy is given by ΔKE=1/2 m*V² +1/2*I*ω²

The energy will be absorbed into that portion of the rotor that is swept by the disc brake pad. We will have to estimate the temperature change of the rotor during the single stop.
This is given the equation
E= m*Cₚ*ΔT
Where,
KE = Kinetic energy
m= mass of the vehicle in kg
V= velocity of the vehicle in m/sec
I= Mass moment of inertia of the front wheel in kg-m²
ω= Angular velocity of the Tire in rad/sec
Cₚ= Specific heat of the steel=540 J/kg.k
The single stop temperature should not be more than 350 degrees

Step 7 and 8: Master cylinder sizing and Booster sizing
The below formulas are used to find out the force required on the brake pedal to stop the vehicle
1. Force on Master Cylinder (TMC) Piston = (Pressure * TMC Area)/ (TMC efficiency)
2. To find the Booster Input force, the following are the conditions
   a. If, Force on piston ≥ Booster saturation force
      Then, {(Force on piston - Booster saturation force) + Input force at saturation}
   b. If, Force on piston ≤ Booster saturation force and Force on piston ≥ Jump in force
      then, {(Force on piston-Jump in force)/(Boost ratio + Threshold force)}
   c. If, Force on piston < Jump in force and Force on piston > Threshold force
      then, Threshold force
3. Brake pedal force = (Booster Input force * Pedal ratio)/Pedal efficiency

Step 9 and 10: Legal requirements
The legal requirements as per IS: 11852 part: 3. The Design must meet all the below criteria as shown in below table

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Vehicle speed V Km/h</th>
<th>Stopping distance ≤0.1V +V²/150</th>
<th>Deceleration m/s²</th>
<th>Pedal force ≤50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type P test with engine</td>
<td>80</td>
<td>5.8</td>
<td>≤5</td>
<td>≤50</td>
</tr>
<tr>
<td>disconnected</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type P test with engine</td>
<td>120</td>
<td>&lt;0.1V</td>
<td>&gt;5</td>
<td>≤50</td>
</tr>
<tr>
<td>connected</td>
<td>= 80% Vmax</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary braking</td>
<td>80</td>
<td>&lt;0.1V</td>
<td>&gt;2.9</td>
<td>≤50</td>
</tr>
</tbody>
</table>
The Adhesion-deceleration coefficient for the front & Rear is given by:

Adhesion deceleration coefficient for Front
= \{(\text{Front actual torque}/\text{Ideal front torque})\times \text{deceleration}\}

Adhesion deceleration coefficient for Rear
= \{(\text{Rear actual torque}/\text{Ideal Rear torque})\times \text{deceleration}\}

The figure 5 and 6 is the adhesion curve both in Unladen and laden, and the importance of this curve is in all the conditions there is only front wheel lock.

*Step 11: Vehicle testing*

The following equipments were used for the vehicle testing:
1. L-400 optical sensor as shown in fig 7
2. DAS-2 (Data acquisition system) as shown in fig 8
3. Pressure transducer as shown in fig 9
4. Pedal effort gauge as shown in fig 10
5. Pedal travel gauge
The vehicle was built to validate the following conditions

a. Unladen Front pressure V/s Rear pressure
A comparative graph of theoretical v/s vehicle testing data has been plotted as shown in fig 11. Unladen front pressure is the pressure in the brake pipeline when the vehicle is driven only by driver. In this the cut-in pressure between both the graphs are within the acceptable criteria (Δ) of ±7 bar.

![Fig 11 Unladen front pressure V/s Rear pressure](image)

1-Vehicle testing data 2-Theoretical data
Fig 11 Unladen front pressure V/s Rear pressure

b. Laden Front pressure V/s Rear pressure
A comparative graph of theoretical data v/s vehicle testing data has been plotted as shown in Fig 12. The laden front pressure is the pressure in the brake pipeline when the vehicle is fully loaded. In this the cut-in pressure between both the graphs are within the acceptable criteria (Δ) of ±7 bar.

c. Pedal travel(PT) V/s deceleration(g) Unladen
A comparative graph of theoretical data v/s vehicle testing data has been plotted as shown in Fig 13. The pedal travel is the travel of the brake pedal in order to stop the vehicle. The acceptance criteria is ±10%.

\[
\text{% Variation} = \left( \frac{\text{PT}_{\text{(Theory)}} - \text{PT}_{\text{(Actual vehicle)}}}{\text{PT}_{\text{(Theory)}}} \right) \times 100
\]

![Fig 13 Pedal travel V/s deceleration (g) Unladen](image)

1-Vehicle testing data 2-Theoretical data
Fig 13 Pedal travel V/s deceleration (g) Unladen

d. Pedal travel V/s deceleration(g) laden
A comparative graph of theoretical data v/s vehicle testing data has been plotted as shown in Fig 14. The pedal travel is the travel of the brake pedal in order to stop the vehicle. The acceptance criterion is ±10%.

![Fig 14 Pedal travel V/s deceleration (g) Laden](image)
e. Regulation validation
The vehicle was tested in Unladen condition against the specifications mentioned in Table-1, the below results which have evolved out of testing. The Table-2, 3, 4 and 5 are for the Unladen and Table-6, 7, 8 and 9 are for the laden

TABLE 2 (All wheel-Engine disconnected)

<table>
<thead>
<tr>
<th>PE(Kg)</th>
<th>Speed</th>
<th>MFDD</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.98</td>
<td>79.97</td>
<td>6.63</td>
<td>Pass</td>
</tr>
<tr>
<td>14.3</td>
<td>79.73</td>
<td>6.95</td>
<td>Pass</td>
</tr>
<tr>
<td>14.78</td>
<td>79.45</td>
<td>7.63</td>
<td>Pass</td>
</tr>
</tbody>
</table>

TABLE 3 (Secondary failure – Front only)

<table>
<thead>
<tr>
<th>PE(Kg)</th>
<th>Speed</th>
<th>MFDD</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.98</td>
<td>79.97</td>
<td>6.63</td>
<td>Pass</td>
</tr>
<tr>
<td>14.3</td>
<td>79.73</td>
<td>6.95</td>
<td>Pass</td>
</tr>
<tr>
<td>14.78</td>
<td>79.45</td>
<td>7.63</td>
<td>Pass</td>
</tr>
</tbody>
</table>

TABLE 4 (Secondary failure - Rear only)

<table>
<thead>
<tr>
<th>PE(Kg)</th>
<th>Speed</th>
<th>MFDD</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.98</td>
<td>79.97</td>
<td>6.63</td>
<td>Pass</td>
</tr>
<tr>
<td>14.3</td>
<td>79.73</td>
<td>6.95</td>
<td>Pass</td>
</tr>
<tr>
<td>14.78</td>
<td>79.45</td>
<td>7.63</td>
<td>Pass</td>
</tr>
</tbody>
</table>

TABLE 5 (Transmission failure - Servo failed)

<table>
<thead>
<tr>
<th>PE(Kg)</th>
<th>Speed</th>
<th>MFDD</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.45</td>
<td>79.45</td>
<td>3.27</td>
<td>Pass</td>
</tr>
<tr>
<td>41.29</td>
<td>80</td>
<td>3.28</td>
<td>Pass</td>
</tr>
<tr>
<td>39.1</td>
<td>79.73</td>
<td>3.08</td>
<td>Pass</td>
</tr>
</tbody>
</table>

TABLE 6 (All wheel-Engine disconnected)

<table>
<thead>
<tr>
<th>PE(Kg)</th>
<th>Speed</th>
<th>MFDD</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.91</td>
<td>79.18</td>
<td>6.18</td>
<td>Pass</td>
</tr>
<tr>
<td>16.5</td>
<td>79.45</td>
<td>6.25</td>
<td>Pass</td>
</tr>
<tr>
<td>14.81</td>
<td>80.27</td>
<td>6.1</td>
<td>Pass</td>
</tr>
</tbody>
</table>

TABLE 7 (Secondary failure - Front only)

<table>
<thead>
<tr>
<th>PE(Kg)</th>
<th>Speed</th>
<th>MFDD</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.62</td>
<td>80</td>
<td>4.14</td>
<td>Pass</td>
</tr>
<tr>
<td>9.79</td>
<td>79.73</td>
<td>3.33</td>
<td>Pass</td>
</tr>
<tr>
<td>8.83</td>
<td>80</td>
<td>3.05</td>
<td>Pass</td>
</tr>
<tr>
<td>42.15</td>
<td>80.27</td>
<td>3.31</td>
<td>Pass</td>
</tr>
</tbody>
</table>
TABLE 8 (Secondary failure - Rear only)

<table>
<thead>
<tr>
<th>PE (kg)</th>
<th>Speed</th>
<th>MFDD</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>35.6</td>
<td>79.73</td>
<td>2.99</td>
<td>Pass</td>
</tr>
<tr>
<td>35.2</td>
<td>79.18</td>
<td>3.03</td>
<td>Pass</td>
</tr>
<tr>
<td>38.67</td>
<td>79.73</td>
<td>3.06</td>
<td>Pass</td>
</tr>
</tbody>
</table>

TABLE 9 (Transmission failure - Servo failed)

<table>
<thead>
<tr>
<th>PE (kg)</th>
<th>Speed</th>
<th>MFDD</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.89</td>
<td>80</td>
<td>3.37</td>
<td>Pass</td>
</tr>
<tr>
<td>43.33</td>
<td>80</td>
<td>3.22</td>
<td>Pass</td>
</tr>
<tr>
<td>42.15</td>
<td>80.27</td>
<td>3.31</td>
<td>Pass</td>
</tr>
</tbody>
</table>

The vehicle has met all the critical tests mentioned in IS: 11853 part: 3 regulation.

IV. CONCLUSION

Hydraulic brake system is one of the most important safety features on many road vehicles today; it has met the manufacturer and customer requirements in addition to legal vehicle Safety Standards. With these procedures we were able to analyse the following:

a. The vehicle will stop in any condition within the brake Pedal effort (PE) of 50 kg as shown in table 2 to 9
b. The stopping distances are within the specification as Per IS: 11852 part 3

The figures 9, 10, 11 and 12 shows that the theoretical and testing results are within the acceptance criteria. Calculations necessary to predict brake balance and key System sizing variables that contribute to performance was briefly discussed and the vehicle was fitted with these configurations.

This methodology can be used as a Design manual which intends to cover steps involved.

ACKNOWLEDGMENT

My special thanks to Dr. A.G. THAKUR (Head of Department), who is my guide and Prof. S.V. Bhaskar (P.G.Coordinator) for their sincere efforts and for their kind guidance especially in selecting and finalizing this seminar topic. They took deep interest in checking the minute details of the report and guided me throughout till the end. They have been a constant source of inspiration to me.

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