Hydraulic brake system performance evaluation methodology for off highway applications: Simulation and Testing correlation

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Abstract

This paper describes a simulation methodology developed for hydraulically actuated brake system performance evaluation and hydraulic system architecture optimization for off-highway applications. It leads to significant engineering efforts, resources, and time to evaluate the system performance through physical tests and challenging to replicate cornering conditions in the field. Hence, it is essential to develop a simulation methodology in a virtual environment to understand the interaction of hydro-mechanical system and its impact on overall system behavior during different braking scenarios. This study adopts a model-based design approach for understanding hydraulic brake system dynamic behavior. This simulation methodology has been developed in a 1D system simulation environment with the right fidelity modeling approach for various modules of braking system to capture the dynamic events. This model includes different hydraulic components for actuation system, mechanical linkages, 1D drivetrain and 3D vehicle model. Vehicle 6-DOF model has been developed and incorporated through coupled simulation to improve the predictability of mean fully developed deceleration (MFDD). This methodology has been correlated with test data acquired on vehicle during different braking scenarios and showing good agreement with test results. This dynamic simulation model helps to understand and predict the potential root cause of system malfunctioning in the early stage of product development cycle. DOE has been performed to assess the impact of various system parameters on braking system performance. This methodology can be used to develop new predictive simulation workflows to address design issues in virtual environment with significant reduction in product development time, cost and risks associated with lab & field tests.

Introduction

Braking system is an essential subsystem of vehicle, which either slow down or stops the vehicle while running on the road. In case of off highway machines brakes also steers the vehicle along with braking functionality. Effectiveness of the braking system primarily depends on response time of its actuation system and operator. Response time of the system can be defined as the time between the actuation of control pedal and the actuator pressure reaching to ~75% of its operating value. Designing of the brake system is very complex and needs several design iterations to finalize the design layout to achieve the optimum design. The conventional approach will lead to higher product development cost and may delay the product deployment to market. Hence it is essential to have virtual methodology for predicting the system performance at early stage of product development cycle [1].

Figure 1 shows architecture of conventional hydraulic brake system which mainly comprises of oil reservoir, push rod, master cylinder, return spring, brake piston cylinder etc. Brake pedal is connected to push rod. When operator pressed brake pedal it pushes the push rod and hence master cylinder. Cylinder then traps the oil in the passage between brake piston and master cylinder which results in increase in pressure on brake piston and hence applying force on the brake. Once the pedal is released the retractor will push the disc to its initial position and brake is released and allow the system to move forward.

Sridhar et. al., describes the brake system valve modeling and prediction of valve dynamic response [2]. Ho, Hon Ping studied the influence of brake system elements design parameters on pedal feel in passenger car using 1 D simulation tool [3]. Kuang et al. developed a hydraulic braking system model using bond graph theory, which is suitable for designing the active vehicle dynamics control system [4]. P Delaigue et al. developed comprehensive vehicle braking system model to predict the vehicle stopping distance under different braking conditions and validated with experimental data from field [5]. Yong Yang et al, developed 1D model of braking system to understand the influence of different factors on system behavior [6]. Hosseinlou M.H. presented the study of minimum safe stopping distance between two vehicles in different weather and road conditions [7]. Rievaj V et.al. studied the impact of the tire inflation pressure on vehicle stopping distance [8].

In summary, the researchers have used different model fidelities based on the availability of resources and objective to understand the braking system behavior. Most of the researchers have considered the brake pedal kinematics, hydraulic actuation system behavior, brake friction, vehicle dynamics and modeled the vehicle with 1D approach to understand longitudinal vehicle dynamics.

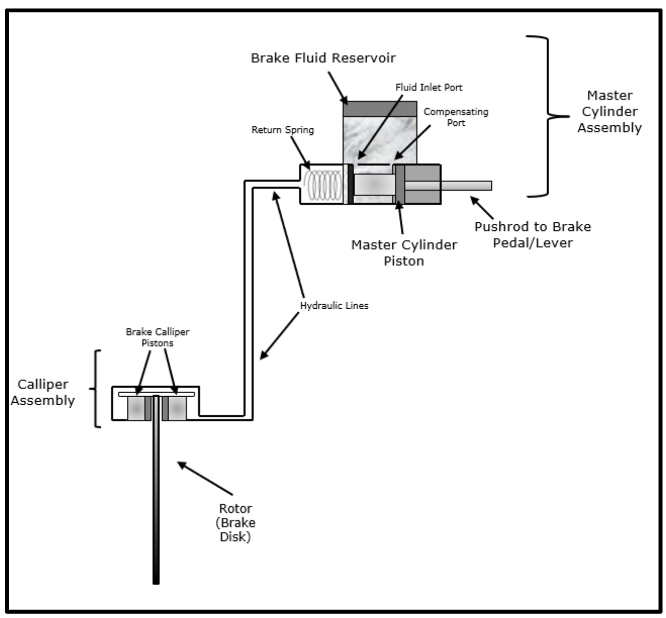

Figure 1. Schematic representation of Hydraulic Braking system

In this paper virtual methodology is proposed to evaluate the performance of hydraulically actuated braking system to evaluate vehicle behavior during braking event. The hydraulic system and its components, brake pedal linkages are modeled with right fidelity to understand the dynamic behavior of braking system. Vehicle is modeled using 1D approach to capture the dynamics during braking event in longitudinal direction. To accommodate the pitching event effect high fidelity model was developed in 3D environment for vehicle system and coupled with 1D hydraulic actuation system.

Virtual Simulation Model Development

This study presents the development and validation of an analytical model of the braking system of an off-highway vehicle as shown in **Figure 2**. The virtual model of braking system includes the brake pedal dynamics, right fidelity nonlinear models for hydraulic system components like pressure regulating valves, check valves, directional valves, non- return valves, piston-cylinders have been developed to capture the necessary system dynamics. To understand the interaction between tire and the road the Pacejka 1989 tire model is used with 1D vehicle approach to captures the longitudinal dynamics. To further improve the accuracy of the results the coupled simulation has been performed to capture the vehicle dynamics with 3D modeling approach which uses Brixius tire model. Brixius tire model was developed using the test data on tractor and utilizing the empirical relations. The friction between the brake friction disc and braking plate is considered to capture the force transmission from hydraulic system to the friction disc. This virtual model uses pedal force, system pressure, engine speed as an input. To understand the braking system performance of the vehicle, the vehicle speed, stopping distance are chosen as an output. MFDD is calculated using vehicle speed and distance travelled.

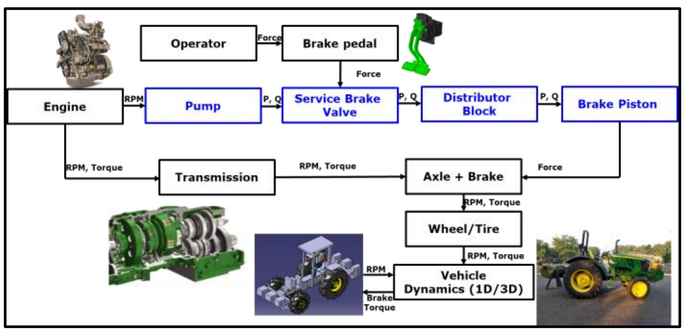

Figure 2. Braking system architecture

This model can be used to evaluate the performance of different hydraulic architectures and assess designs for optimum brake performance. Following section describes modeling approach for various subsystem modules as shown in **Figure 3**.

Service Brake valve: Service brake valve is an important component of the braking system which translates mechanical energy into hydraulic energy. Brake valve is operated when the brake pedal is pressed & its function is to build pressure in the hydraulic system to generate braking torque. This valve mainly consists of check valve, pressure equalizer, pilot operated valve, brake oil reservoir etc. Valves are modeled using geometry to capture the spool dynamics, oil flow and pressure variation during brakes apply and release events.

Distributor block: Distributor block in the brake hydraulic system cater to the pressurized oil distribution in the system. This block controls the priority between service and secondary/park brake to supply the pressurized oil using combination of shuttle valve, check valves and orifices. It also plays an important role of supplying hydraulic oil to trailer brakes before supplying to the service brakes. Valves are modeled using geometry to capture the spool dynamics, oil flow and pressure variation during brakes apply and release events.

Oil immersed axle brake assembly: In conventional axle design the brake assemblies are present on both left and right sides of rear axle shafts. This consists of actuation piston, friction discs and retractor. Brake discs with friction lining material apply the resisting torque on the axle shaft through splined connection to reduce the vehicle velocity. The retractor provides the mechanism to remove the oil pressure on brake piston when brake pedal is released.

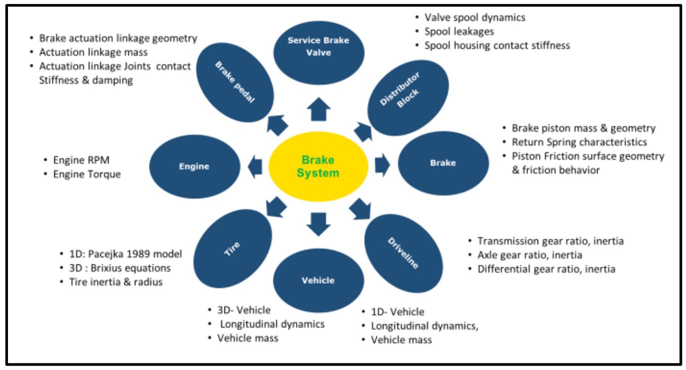

Figure 3. Braking system model components

Driveline: Driveline is modeled to capture the speed reduction from engine to the axle. This includes gear ratios of transmission, differential and final drive.

Vehicle dynamics: Two approaches have been studied for modeling vehicle dynamics, 1D & 3D. 1D vehicle & tire model developed initially represent simplified behavior to capture the longitudinal vehicle dynamics. High fidelity 3D vehicle dynamics model developed later in virtual lab environment to captures detailed vehicle dynamics which includes vehicle static reactions, radial tire stiffness, pitch, and roll motions.

Tire: Tires of the vehicle are key elements contributing into the dynamic behavior of vehicle during braking event. As the focus of study is to understand the braking performance of the vehicle in longitudinal direction hence the Pacejka 1989 tire model is used in 1D approach. In Virtual lab the tire road interaction is modeled using Complex tire model. This complex tire model is developed using Brixius equations which are developed with the help of test data acquired on tractor machine with different tires and soil interaction.

Test Data Acquisition & Instrumentation

To better understand the braking system behavior and verify the virtual methodology, physical tests and data acquisition have been conducted on the tractor in actual field applications. The sensor locations to measure different parameters have been decided based on the initial simulation results, experience, and feasibility of sensors installation as shown in **Table 1. Figure 4** shows the tractor prepared to collect test data from test measurement site at VRDE. Force and displacement sensors have been installed on the brake pedal as shown in **Figure 5**. Vehicle velocity and the distance traveled was measured with the help of GPS installed on the vehicle. The parameters that are measured to understand the vehicle behavior during braking event are brake pedal force, brake pedal travel, vehicle speed, stopping distance. **Figures 6, 7 & 8** shows variation of above parameters during the braking event in field test. The parameters acquired on the tractor are utilized to for comparison with simulation model. This data helped to enhance the confidence on the methodology developed for brake system performance evaluation.

Table 1. Sensor types and arrangements on Vehicle

Sensor Type	Sensor location	Sampling rate
Displacement sensor	Brake foot pedal	200 Hz
Force sensor	Brake foot pedal	200 Hz
GPS- Vehicle speed	Vehicle body	100 Hz
GPS-Stopping distance	Vehicle body	100 Hz

Figure 4. Braking test photo

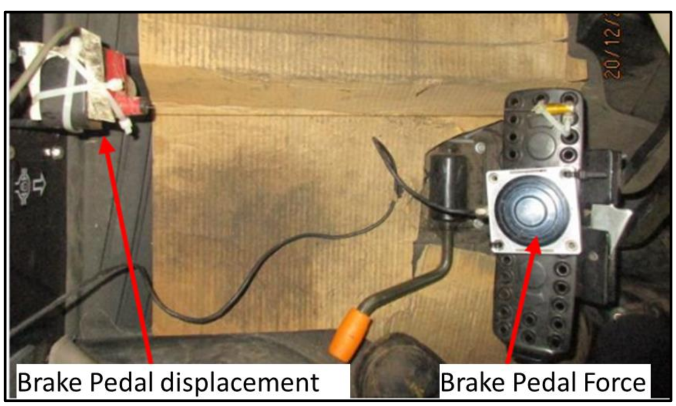

Figure 5. Pedal force and displacement sensor

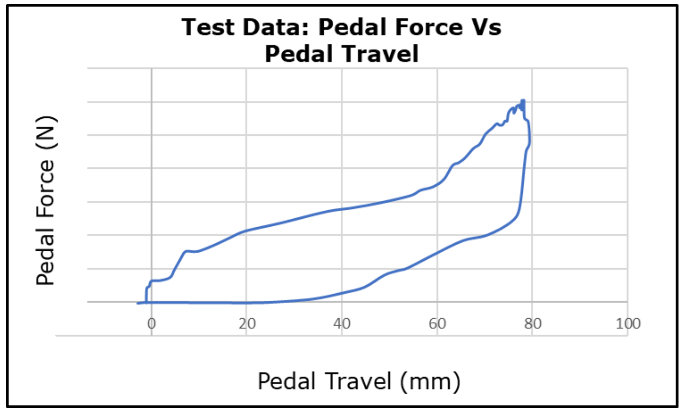

Figure 6. Test data: Brake Pedal force Vs Pedal Travel

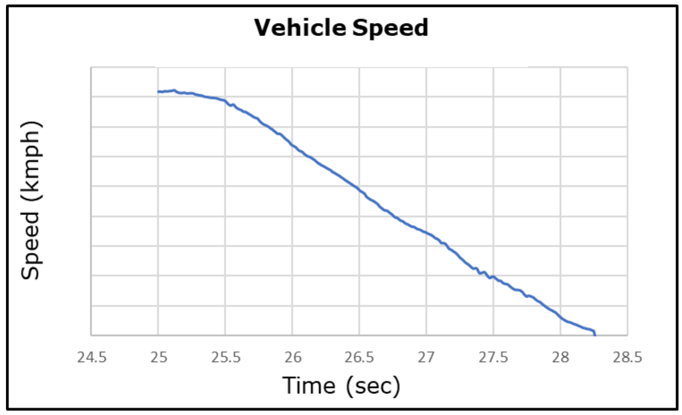

Figure 7. Test data: Vehicle speed

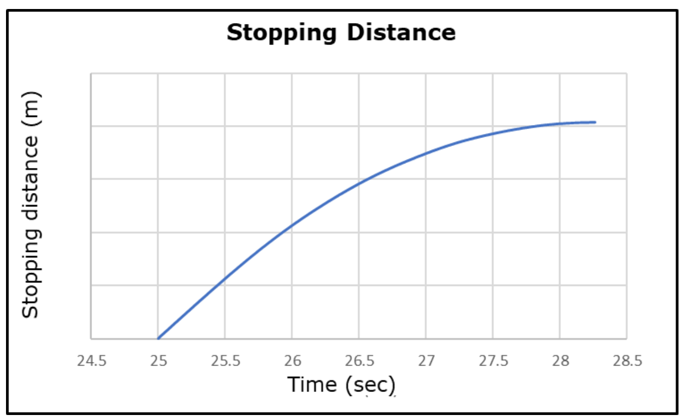

Figure 8. Test data: Stopping Distance

Analytical Model Correlation with Test Data

To validate the virtual methodology, several braking events have been performed in the field. Simulation also be carried out with similar input conditions to reproduce the real-world usage scenario and test conditions for correlation with test data. Simulation results attained from 1D & 3D (coupled simulation) simulation approach and compared with test data. It has been observed that the 3D co-simulation approach helped to improve the prediction accuracy by ~7% with respect to 1D simulation approach and aligned with the test data observations as shown in **Figure 9, 10, 11**.

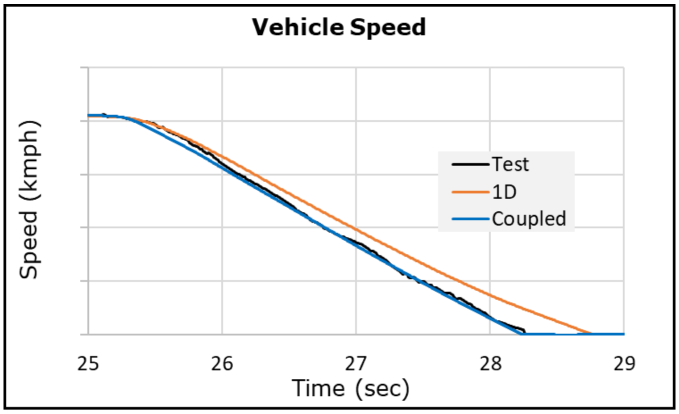

Figure 9. Test Vs Simulation: Vehicle Speed

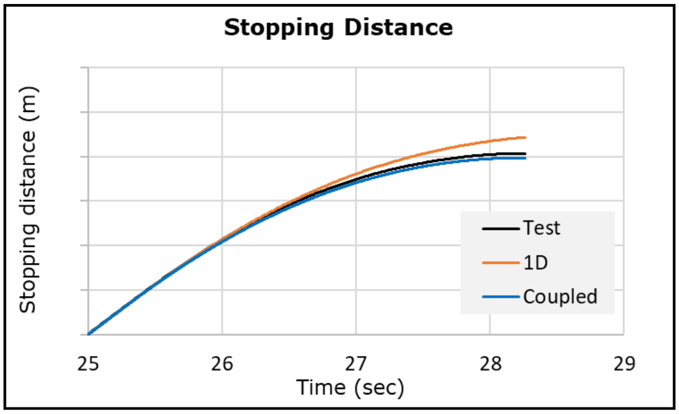

Figure 10. Test Vs Simulation: Stopping Distance

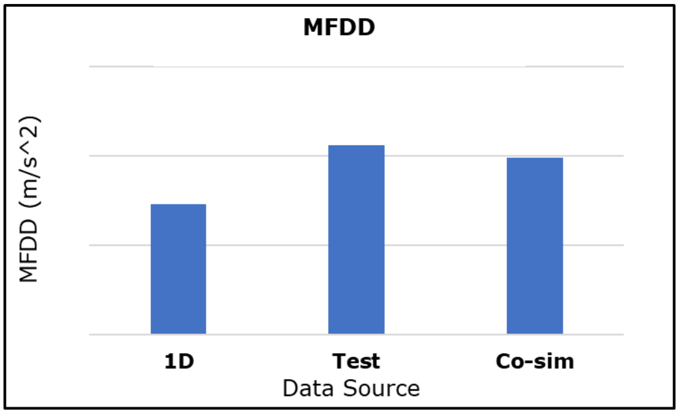

Figure 11. Test Vs Simulation: MFDD

Result and Discussion

Developed simulation methodology has been deployed to evaluate the different scenarios as well as for parametric study to understand the effect on system behavior due to change in oil temperature, leakage, retractor stroke and aeration.

Parametric study of brake hydraulic system components:

Sensitivity study was performed to understand the impact of various hydraulic and driveline system parameters to evaluate the dynamic braking response. Pedal force data from the test is used as an input to simulation model to evaluate the pedal travel through simulation.

Effect of Retractor stroke: Retractor stroke plays significant role to control the pedal force and need to investigate its impact on the operator comfort. Retractor stroke is the distance travelled by retractor after brake pedal is pressed. It has been observed that the pedal travel is directly proportional to the retractor stroke and concluded that the with increase in retractor stroke the pedal travel will also increase as shown in **Figure 12**.

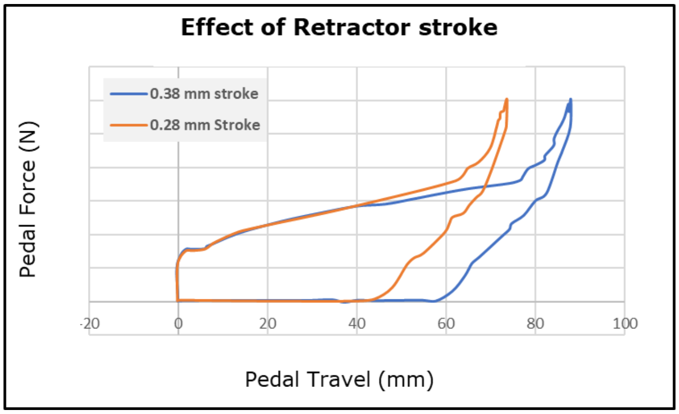

Figure 12. Effect of Retractor stroke

Effect of Oil Temperature: Sensitivity analysis also be performed to understand the effect of oil temperature which mainly affect the oil properties. It has been observed that the pedal travel is directly proportional to the oil temperature and concluded that the with increase in oil temperature the pedal travel will also increase as shown in **Figure 13**. This may lead to adverse effect on operator comfort.

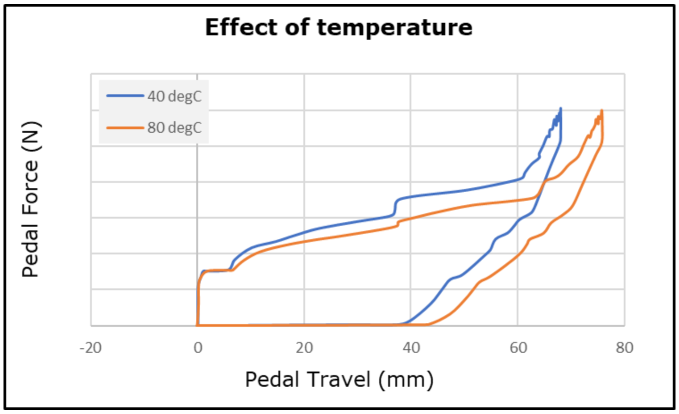

Figure 13. Effect of oil temperature

Effect of Aeration %: Aeration is the air content in the oil and significantly affects the oil properties. It has been observed that the pedal travel is directly proportional to the aeration percentage (%) and concluded that the with increase in aeration % the pedal travel will also increase as shown in **Figure 14**.

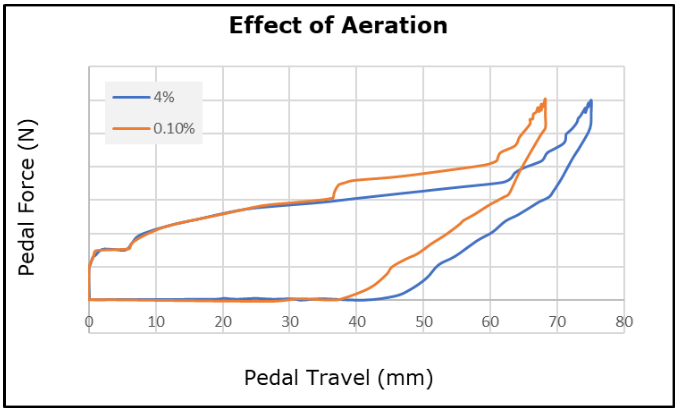

Figure 14. Effect of aeration

Effect of Seal Leakage: Leakage is a critical factor to achieve the hydraulic system performance and higher leakage may deteriorate the hydraulic system performance and efficiency. In this study seal leakage was incorporated in simulation model to understand its impact on braking performance. It has been observed that the pedal travel is directly proportional to the system leakage and concluded that the lesser the seal leakage, the lower the operator effort to achieve better braking performance as shown in **Figure 15**.

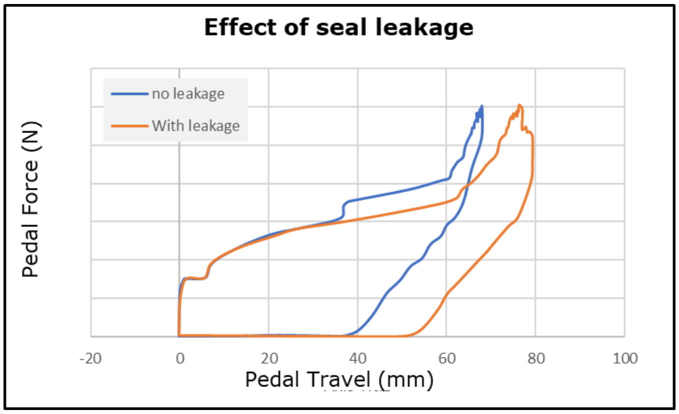

Figure 15. Effect of leakage

Summary/Conclusions

This paper presented the model-based system design approach to assess the vehicle braking system performance and parametric study to understand the system dynamic response. This study adopts modeling approaches, 1D and 3D-coupled simulation to evaluate braking system performance. The model captures dynamic behavior of hydraulic system and longitudinal vehicle dynamics. The vehicle dynamics is captured through 1D modeling approach using Pacejka tire model and enhance the modeling fidelity by using 3D-coupled simulation approach by incorporating Brixius tire model to accommodate pitching effect. This virtual simulation methodology helps to optimize the hydraulics & mechanical system performance and limit the experimental engineering efforts, cost and time.

1D and 3D simulation methodology has been compared with test data and showing very good agreement with test observations.1D simulation approach shows ~85% correlation. It has been observed that the coupled simulation approach helps to improve the correlation by ~7% and achieve the overall correlation of ~92%.

DOE study was performed to assess the impact of various components of hydraulic and mechanical system key parameters like retractor stroke, oil temperature, aeration and seal leakage. It has been concluded that all the parameters are directly proportional to the pedal travel and influence the braking performance.

It has been concluded that the coupled simulation methodology has better virtual predicting capability as compared to the 1D simulation approach. However, 1D simulation approach has less computational time compared to coupled simulation and would be beneficiary to adopt in preliminary design phase. Based on the literature study there is the possibility to understand the impact of several other system parameters like pedal length, brake valve piston geometry on braking performance.

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Definitions/Abbreviations

DOF	Degree of Freedom
MFDD	Mean Fully Developed Deceleration
DOE	Design of Experiments
VRDE	Vehicles Research and Development Establishment