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Numerical Simulation of Designing a Braking System by Comparing Pressure in Minibus Type Vehicle

Naufal Aflah Hibatullah[1 *], Adri Maldi Subardjah[2]

[1] Master Degree Program, Department of Mechanical Engineering, Institut Teknologi Bandung
Jalan Ganesha No. 10, Bandung, Indonesia-40132

[2] Department of Mechanical Engineering, Politeknik Negeri Bandung
Jalan gegerkalong hilir, Bandung, Indonesia-40012

**Corresponding author: naufal.7.aflah@gmail.com*

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Abstract

The braking system is crucial in maintaining the vehicle's safety to avoid fatality. However, designing a vehicle braking system can take significant time and energy. Hence, a method to design a braking system that requires less time and energy is necessary. The vehicle specifications will affect the braking design process in designing a braking system. In addition, the existing government regulations limit the braking capacity that must be achieved during the braking process. These two things become the limitations in designing an optimal braking system. The design process is carried out by determining the required pressure for the braking process and the pressure generated during the braking process. The generated pressure must exceed the required pressure for the braking system design to work appropriately. The conditions mentioned earlier can be achieved by iterating and selecting the standard component. A case study in the form of braking system design has been carried out where the braking system can generate a pressure of 4.14 MPa and requires a pressure of 3.13 MPa and 2.34 MPa at the front and rear caliper on a vehicle weighing 78.48 kN to decelerate 5 ms^{-2} as required in Indonesia government regulation. A comparison is made with other methods proposed by other researchers to ensure the proposed method can be applied to various conditions. The comparison results show that the proposed method can be applied to various conditions. Moreover, the proposed method can minimize the difference in pressure between the generated and the required pressure to avoid overdesign.

Keywords: Braking system design, vehicle deceleration.

1. Introduction

The braking system is a vital component in the braking process to decelerate a vehicle, maintain the speed of vehicles on a downhill road, and conserve vehicle stability. Malfunction of the braking system will endanger passengers and result in fatalities [1, 2]. The importance of a braking system in a vehicle promotes the government to make regulations to prevent accidents caused by braking system failure. Indonesian Government Regulation number 55 year 2012 concerning vehicles, article 67 paragraph 1 declares that vehicle braking system must be capable of deceleration at least 5 ms^{-2} [3]. The regulation must be a significant concern in the design process of a braking system to ensure passenger safety.

In general, the braking mechanism works when the foot presses the pedal. Then the compressive force is transmitted to the master cylinder, wherein the master cylinder converts the compressive force into a change of fluid pressure. The change in fluid pressure at the master cylinder will be forwarded to the brake actuator using brake pipes. The brake actuator, a caliper-type actuator, will convert pressure into force. The generated force will cause friction between the brake pad and the disk. This frictional force results in a drag force on the wheels, making the vehicle decelerate [2, 4]. Vehicle deceleration will depend on friction behavior between the tire and the road. There is a possibility of slipping between the tire and the road, resulting in an accident; however, an anti-lock braking system (ABS) is developed

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to minimize the accident by lessening the slip factor between the tire and the road by controlling the wheel speed. The problem with ABS is that it is a very non-linear system, unpredictable, and hard to tune [5-7], so supposing an optimal ABS control system is necessary for designing a braking system. With an optimal ABS control system, optimal decelerating capacity can be achieved.

In the current research trend, regenerative braking is in the limelight because of its capability to convert wasted energy in braking into electrical energy [8-11]. However, regenerative braking can only be applied to hybrid or electric vehicles. Therefore, fossil fuel vehicles' most common braking systems are hydraulic braking systems. There are several studies on designing a hydraulic braking system, such as studies conducted by Soni et al. in designing an unboosted braking system for a racing car to reduce total vehicle weight [12]. Moreover, Diwakar et al. designed an unboosted hydraulic braking system for All Terrain Vehicle (ATV) by comparing generated and required torque from the braking process [13]. Although both research explain the ways and methods of designing a braking system, it is more complex than it seems. Designing a braking system requires conducting calculations starting from the input force on the brake pedal until it causes the vehicle to experience a deceleration by a certain value sequentially. In addition, varied specifications of the braking system components result in the need for iterations to choose the right design. Hence, the braking system design process will take significant time and energy.

This research elaborates on designing a braking system by comparing pressure generated and pressure required along the braking process while selecting a braking component from an existing database. This method is applied to a case study in designing a minibus vehicle with a fully loaded weight of 78.48 kN, wheelbase distance of 4.2 m, with a center of gravity position at the center of the vehicle with 0.6 m distance from the ground. The designing process will determine how much pressure is generated in the master cylinder from the pedal force. Then it will be compared with the pressure required to decelerate the vehicle at $5ms^{-2}$ as mentioned in government regulation. These two kinds of pressures will be compared; if the generated pressure is less than the required pressure, we must re-iterate the process by changing some variables until the generated pressure is greater than the required pressure.

2. Research Methodology

In designing a braking system, knowing the braking mechanism will help determine the workflow of the design process. Braking occurs when the foot presses the pedal then the foot force is converted to a greater force by the lever mechanism in the pedal. If necessary, the converted force is then forwarded to the brake booster to increase the force before being converted to pressure in the master cylinder. The pressure in the master cylinder will be forwarded to the brake actuator, a caliper-type actuator. The pressure from the master cylinder will push the brake pad piston in the caliper until the brake pad presses against the brake rotor. The pressure from the fixed brake pad and the rotating brake rotor will generate friction which will counter wheel rotation so that the vehicle decelerates. The decelerating ability of a vehicle is caused by its braking system and the friction behavior of its tire and the road, sliding or not. A sliding behavior will decrease the braking capacity, making stopping distance and stopping time longer. However, using ABS can avoid this behavior and make the braking system work in the best condition [2, 4, 14]. Besides the braking mechanism, the vehicle specification and government regulation will be substantial in the braking system design process. Those will restrict some parameters in the calculation and component selection process. Vehicle specification will affect the dynamic load distribution of each wheel and the pressure required to decelerate per government regulation. Calculating each step in the braking mechanism is necessary, and iteration is necessary to select the ideal braking component. However, in such a way, it would take a significant amount of time and energy to obtain a complete braking system design. Therefore, separating the working process into two parts, calculating generated pressure and pressure required, then comparing generated pressure and pressure required will simplify the design process. Suppose the generated pressure has higher value than the required pressure. In that case, the braking system with the selected component can be applied to the vehicles, however when the generated pressure has lower value than required pressure, there is a need to do some iteration by changing selected component until the generated pressure is greater than the required pressure. To understand the method more straightforwardly, see the flowchart shown in Figure 1.

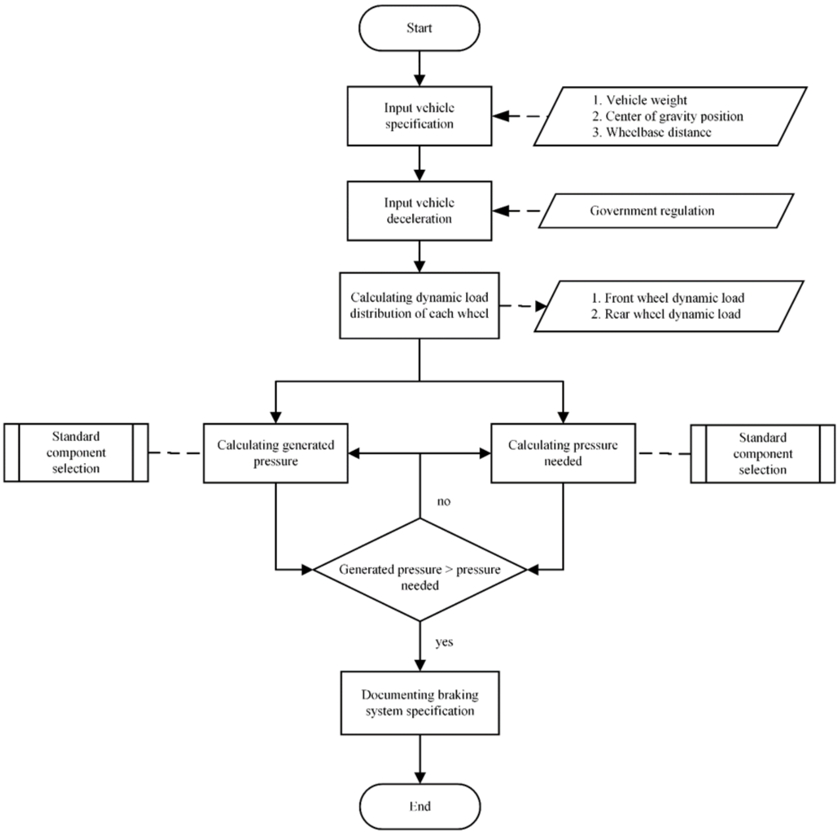

Figure 1. Flowchart of braking system design method

3. Design Calculation

The design of the braking system will be determined by design calculation and component selection along the iteration process. Based on the flowchart from Figure 1, the design calculation will determine the dynamic load distribution, the pressure required to decelerate, and the pressure generated when the braking process happens. The dynamics load distribution will influence the required pressure directly. Hence determining dynamic load distribution is the first step in the design calculation. After determining the dynamic load distribution, calculating the pressure required and the pressure generated can be done simultaneously, then comparing both pressures along the required iteration process is necessary. If the generated pressure is greater than the pressure required, a further iteration process is not required.

3.1 Dynamic Load Distribution

Calculating the dynamic load of each wheel is a must before determining a braking system because it will determine the friction force between the tire and the road, which determines the vehicle's deceleration. The vehicle's weight, center of gravity, wheelbase, and deceleration will define the dynamic load based on its free body diagram [2, 15]. More details about the free body diagram of dynamic load distribution can be seen in Figure 2.

$$\sum M_A = 0$$

$$F_{dyn_f} wb - F_i h - W(wb - l) = 0$$

$$F_{dyn_f} = \frac{F_i h + W(wb - l)}{wb} \tag{1}$$

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$$\sum M_B = 0$$

$$W(wb - l) - F_i h - F_{dyn_r} wb = 0$$

$$F_{dyn_r} = \frac{Wl - F_i h}{wb} \quad (2)$$

where:
wb - wheelbase distance [m]
l - front wheel distance to the center of gravity [m]
h - the center of gravity distance with the ground [m]
F_i - inertia force [N]
F_{dynf} - dynamic load at front axle [N]
F_{dynr} - dynamic load at rear axle [N]
W - vehicle's weight [N]

Based on vehicle specification, the vehicle weight is 78.48 kN, wheelbase distance of 4.2 m, with the center of gravity position at the vehicle's center which is 2.1 m from the front wheels with 0.6 m distance from the ground. Following the government regulation, the vehicle must have a deceleration of at least 5 ms^{-2}, and the inertial force of the vehicle will be 40 kN.

Dynamics loading at each axle can be determined by calculating the free body diagram of the vehicle with zero moment at each contact point [2, 15].

Because there are two wheels at each axle, the dynamic force at each axle will be divided by two for each wheel. Then, the normal force at the front wheel will be 22.48 kN, and the normal force at the rear wheel will be 16.77 kN.

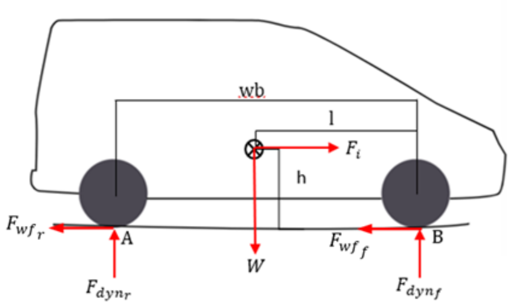

Figure 2. Free Body Diagram in a Braking Process Modified from "The Influence of the Cargo Weight and Its Position on the Braking Characteristics of Light Commercial Vehicles" [15]

3.2 The Pressure Required in the Braking Mechanism

The normal force from dynamic loading distribution will cause friction between the tire and the road, and that friction will cause the vehicle to decelerate. The friction force between the tire and the road will be based on its friction coefficient—theory of ground vehicle by JY. Wong [16] mentioned the tire-road friction coefficient in multiple types of roads and its condition. More detail can be viewed in Table 1.

Table 1. Average Values of Road Adhesion Coefficient [16]

Average Values of Coefficient of Road Adhesion		
Surface	Peak Value (μ_p)	Sliding Value (μ_s)
Asphalt and Concrete (dry)	0.80-0.90	0.75
Asphalt (wet)	0.50-0.70	0.45-0.60
Concrete (wet)	0.80	0.70

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Gravel	0.60	0.55
Earth road (dry)	0.68	0.65
Earth Road (wet)	0.55	0.40-0.50
Snow (hard-packed)	0.20	0.15
Ice	0.10	0.07

Minibus usually operates on a city road made of asphalt. Assuming the ABS works optimally without sliding, the friction happens at its peak value and the friction coefficient between the tire and the road will be 0.80. Regarding normal force in the tire and its friction coefficient, the friction force at the front wheel will be 17.89 kN, and at the rear wheel will be 13.41 kN. This friction force results from the braking system mechanism that holds the wheel motion with friction force between the brake pad and its rotor. The brake pad is located at a distance, so the friction between the brake pad and the rotor will generate a torsion counter with the torsion generated from the tire's friction and the road. The free-body diagram will be shown in Figure 3.

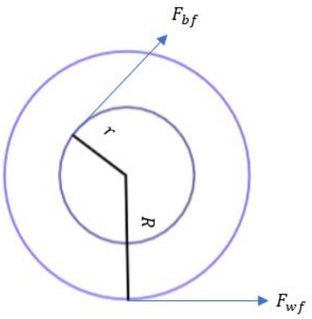

Figure 3. Free Body Diagram of Moment in the Wheel

From Figure 3, a formula can be developed.

$$F_{wf}R = F_{bf}r$$

$$F_{bf} = \frac{F_{wf}R}{r} \tag{3}$$

where:

F_{wf} - wheel friction force [N]
F_{bf} - friction force between brakes pad and brakes rotor [N]
R - Wheel radius [m]
r - distance of the brake pad to the center of the wheel [m]

In this case, standard component selection will determine the calculation result. Iterating optimum wheel size and rotor size will determine how much friction force is needed between the brake pad and brake rotor. With 315/40 R18 wheel size and a rotor diameter of 0,381 m with an effective radius of 0,1702 m, the friction force between the brake pad and the rotor at the front wheel will be 37.21 kN and 27.89 kN at the rear wheel.

The friction force generated in the brake pad will be influenced by friction material and the normal force between the brake pad and rotor. The friction material will determine the friction coefficient of the brake pad and the rotor. Based on SAE J866-2012, the friction coefficient of a braking system has its classification; road vehicles usually use the EE code letter, which has a friction coefficient value of 0.35. More detail in Table 2.

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Table 2. Friction Coefficient Code Letter [17]

Code Letter	Friction Coefficient
C	Not over 0,15
D	Over 0,15 but not over 0,25
E	Over 0,25 but not over 0,35
F	Over 0,35 but not over 0,45
Code Letter	Friction Coefficient
G	Over 0,45 but not over 0,55
H	Over 0,55
Z	Unclassified

The number of contact surfaces will determine each pad's friction force other than the friction coefficient. The brake pad uses a clamping mechanism to keep the rotor stable when braking, so there will be a minimum of two contact surfaces and an even number of brake pads from one caliper assembly. More detail in Figure 4.

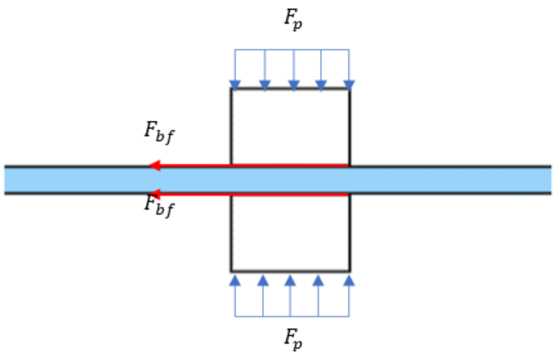

Figure 4. Brake Pad and Rotor

From Figure 4, a formula can be developed.

$$F_p = \frac{F_{bf}}{n\mu_{brake}} \tag{4}$$

where:

F_p - caliper piston push force [N]
n - number of brake pads in one caliper assembly (even number)
μ_{brake} - brake friction coefficient

With a friction coefficient value of 0.35 and the number of brake pads is two, the pressing force of the brake pad at the front wheel is 53.16 kN and 39.84 kN at the rear wheel.

After computing the pressing force of the braking system at each wheel, we can calculate the pressure required in the braking system by using pascal's law. By selecting a caliper with a total piston caliper area of 0.017 m^2 at each brake pad, the pressure required by the braking system in the front wheel is 3.13 MPa, and 2.34 MPa at the rear wheel. The pressure at the front wheel is greater than the rear wheel, so selecting the pressure at the front wheel as the pressure required in the braking system is necessary.

3.3 Pressure Generated

The braking mechanism starts with the foot pressing the pedal, and it will be increased by the lever mechanism in the pedal assembly. Usually, the leverage ratio is mentioned in the catalog.

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However, if it is not listed, the ratio can be calculated by comparing the distance of the input force and the output force to the pivot point.

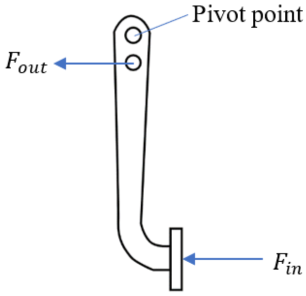

Figure 5. Pedal Force Diagram

The leverage mechanism will generate output force with respect to the input force and the leverage ratio.

$$F_{out} = F_{in}x \tag{5}$$

where:

F_{out} - pedal output force [N]
F_{in} - pedal input force [N]
x - pedal ratio

Limpert states that a brake system should be designed in concern with maximum pedal force between 445-489 N; on the other hand, Puhn states that designing a braking system must consider the braking effort exerted by the driver to achieve maximum deceleration. Usually, a braking system is designed for about 333 N [2, 4]. Usually, the pedal ratio varies between 6 and 7 for an unboosted braking system [18]; the ratio selected is 6.25. Concerning pedal effort and 6.25 pedal ratio, the output force from the pedal will be 2081.25 N. The force will be forwarded and converted into pressure by the master cylinder. Converting the force into pressure will depend on the master cylinder piston diameter. Based on pascal's law, pressure will directly be proportional to the applied force and inversely proportional to the area affected.

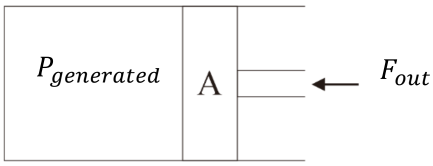

Figure 6. Master Cylinder Schematic Pressure

$$P_{generated} = \frac{F_{out}}{A} \tag{6}$$

where:

$P_{generated}$ - pressure generated by master cylinder [Pa]
A - cross-section area of the master cylinder's piston [m^2]

Iteration is needed to find the optimum diameter of the master cylinder piston diameter to satisfy that generated pressure is greater than the pressure required. The master cylinder with a cross-section piston area of 503 mm^2 is selected, generating a pressure of 4.14 MPa. With this result, the pressure generated is greater than the pressure required in the braking system.

4. Discussion

This paper describes how to design a braking system by comparing the generated pressure with the pressure required during the braking process. The generating pressure is desired to be greater than the pressure required during the braking process. To achieve this condition and avoid overdesign, the iteration of multiple standard components is required. The iterated components are pedal, master cylinder, caliper assembly, brake rotor, wheel, and tire. The iteration data is selected from the various catalog to choose suitable components for an optimal braking system. An unboosted braking system is selected for a vehicle with a fully loaded weight of 78.48 kN, wheelbase distance of 4.2 m, with a center of gravity position at the center of the vehicle which is 2.1 m from the front wheels with 0.6 m distance from the ground. An unboosted braking system is selected because a booster is not required to increase the generated pressure. An unboosted braking system with a caliper-type actuator at each wheel, requires 3.13 MPa pressure in the front caliper and 2.34 MPa pressure in the rear caliper to decelerate 5 m/s^2. Also, the generated pressure is 4.14 MPa, which is greater than the pressure required to decelerate at the front or rear caliper assembly. The specification of the braking system is as follows in Table 3.

Table 3. Braking System Specification

Component	Specification		Unit
	Detailed Specification	Value	
Pedal	Pedal ratio	6.25	-
	Pedal length	297.43	mm
Master cylinder	Piston area	506	mm^2
Brake caliper assembly	Piston area	5612.89	mm^2
	Number of pistons	6.00	-
Brake rotor	Rotor diameter	406.40	mm
	Rotor width	35.05	mm
Tire	Tire diameter	709.00	mm
	Tire width	315.00	mm

The specification above is one of many possible specifications because if one component is changed, another component may be changed while fulfilling the design specification. Hence, the solution of braking design will not be unique because there are multiple possibilities for selecting the standard component, and the use of existing catalogs influences the standard component selection.

Comparing the methods in this study with existing methods in other papers is necessary to prove that these methods can be applied to various cases. Soni et al. and Diwakar et al. research was recalculated using the proposed method; if the results of the proposed method show that the pressure generated is greater than the required pressure on the front and rear calipers, then the proposed method can be applied to various cases. More detail can be viewed in

Table 4.

Table 4. Data and Calculation of the Proposed Method

Vehicle and Braking System Specification	Research conducted by			Unit
	Soni et al. [12]	Diwakar et al. [13]	This work	
Vehicle mass	220.00	207.26	8000.00	kg
Wheelbase	1.64	1.27	4.20	m
Cog distance from front wheel	0.93	0.71	2.10	m
Cog distance from road surface	0.35	0.55	0.60	m
Gravity coefficient	9.81	9.81	9.81	ms^{-2}
Vehicle weight	2.16	2.03	78.48	kN

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Vehicle deceleration	4.93	6.67	5.00	ms^{-2}
Effective radius of the wheel	203.20	292.10	354.50	mm
Effective radius of the disk rotor	78.75	70.00	170.20	mm
Piston area in master cylinder	284.90	285.90	506.00	mm^2
Total piston area in front caliper	530.66	907.92	33677.34	mm^2
Total piston area in rear caliper	530.66	804.20	33677.34	mm^2
Friction coefficient between road and tire	0.70	0.68	0.80	-
Friction coefficient between disk and brake pad	0.40	0.34	0.35	-
Pedal force	2.00	0.30	0.33	kN
Pedal ratio	2.50	7.00	6.25	-
Calculation from proposed method				
Generated pressure	17.55	7.35	4.14	MPa
Required pressure in front caliper	4.98	6.86	3.13	MPa
Required pressure in rear caliper	3.02	1.50	2.34	MPa
Conclusion	The proposed method can be applied	The proposed method can be applied	The proposed method can be applied	

Based on

Table 4, the braking system designed by Soni et al. generates a pressure of 17.55 MPa and requires a pressure of 4.98 MPa at the front caliper and 3.02 MPa at the rear caliper. Moreover, the braking system designed by Diwakar et al. generates a pressure of 7.35 MPa and requires a pressure of 6.86 MPa at the front caliper and 1.50 MPa at the rear caliper. The calculation results indicate that the proposed method is proven to be applicable in solving the research conducted by Soni et al. and Diwakar et al., thus showing that the proposed method can be applied to various cases. Hence, the braking system designed by this work is validated and can be used on a vehicle with a weight of 78.48 kN with the center of gravity at the center of the vehicle, which is 2.1 m from the front wheel and 0.6 m from the road surface. Moreover, the difference between the generated and required pressure in the braking system design proposed by this work has a smaller value when compared to the braking system design proposed by Soni et al. and Diwakar et al., so the proposed method may avoid overdesign in the braking system design, hence may lower the cost of the braking system.

5. Conclusion

The design process has been carried out to obtain a braking system that can work to certain vehicle specifications. The design process consists of determining the dynamic load distribution of the vehicle, the pressure required in the braking system, and the pressure generated in a braking system. Iterating and selecting standard components are necessary to ensure the generated pressure exceeds the required pressure. The braking system design proposed in this research generates 4.14 MPa pressure, and requires 3.13 MPa pressure at the front caliper and 2.34 MPa pressure at the rear caliper of a vehicle with a weight of 78.48 kN to decelerate about 5 m/s^2, which is the minimum threshold limit as stated in the Indonesia government regulation number 55 year 2012 concerning vehicles, article 67 paragraph 1. The standard component mentioned before has proven to meet the requirements as a braking system that works on specific vehicles. However, that does not mean the vehicle can only use the braking system with the mentioned component specifications. The vehicles may use different component specifications on condition that the generated braking system pressure is greater than the required braking system pressure. The generated pressure in each research exceeds the required pressure. Hence, the proposed method is proven applicable to various cases. Moreover, the proposed method can ensure that the generated pressure has slightly greater value than the required pressure, hence may avoid overdesign. The design process focused on design calculation in the theoretics area, which is usually slightly different from the practical area or real life, so it is necessary to do experiments that refer to design calculation in this paper for future works.

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