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Design Explorations on the Brake Force Distributions of a Motorbike

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ABSTRACT

The braking system is crucial for motorbike safety, as effective braking ensures both deceleration and stability. This study investigates the influence of the deceleration rate and the combined biker and pillion load on the optimal distribution of the braking force of a motorbike. A full factorial experimental design was employed using Altair HyperStudy to evaluate the influence of key parameters on braking-force distribution. The study considered three design factors: deceleration (0.1 g, 0.55 g, and 1.0 g), biker mass (50 kg, 75 kg, and 100 kg), and pillion mass (0 kg, 50 kg, and 100 kg). Results indicated a significant positive linear relationship between these parameters and brake forces, with deceleration as the most influential factor. An increase in deceleration resulted in a substantial rise in front brake force, up to 1753.22 N, while biker and pillion masses increased front brake force by 241.22 N and 350.69 N, respectively. Interaction effects revealed that the deceleration, in combination with the pillion load, produced a front brake force of 2226.64 N at 1g deceleration, while biker interaction resulted in 2091.47 N. For rear brake force, deceleration and pillion interaction yielded 64.28 N, highlighting its sensitivity to pillion at higher decelerations. Analysis of Variance (ANOVA) confirmed the statistical significance of all parameters, emphasizing deceleration as critical. Optimal brake force distribution relies on deceleration, necessitating balanced braking to enhance efficiency and safety, achievable through synchronized braking mechanisms like the Concurrent Brake Actuator (CBA).

Keywords: Design Exploration; Brake Force; Distribution; Motorbike; DOE.

Abbreviations

CBA	Concurrent brake actuator
ANOVA	Analysis of variance
DOE	Design of experiment
CG	Center of gravity

1.0 INTRODUCTION

The braking system is the paramount subsystem within the broader category of primary safety mechanisms [1]. In motorbikes, the braking system decelerates and stops their motion, ensuring that they remain stationary when not in motion. The principal purpose of a braking system is to guarantee the safe cessation of a motorbike. The mechanism for engaging the motorbike's brakes differs between the front and rear systems. A hand-operated lever activates the front brake, whereas the rear brake is engaged through a foot-operated pedal system. The motorbike is equipped with a separate braking system for each wheel. Utilizing a front-wheel brake will not only yield substantial deceleration which reduces stopping distance, but it also triggers the remarkable transfer of load from the rear [2]–[4]. This transfer significantly affects the rear braking capabilities, potentially resulting in riding instability or loss of control.

In contrast, using the rear brake solely does not cause the phenomenon of load transfer. However, using a single rear brake increases the likelihood of wheel skidding, thereby reducing stopping power and stability [5]–[7]. To achieve optimal braking efficiency, it is necessary to engage both brakes simultaneously. This practice yields several advantages, such as enhanced deceleration, reduced stopping distance, wheel locking, and rear-wheel lift prevention. When decelerating, bikers must distribute and regulate the required braking force on both brake systems [8]. The acquisition of expertise in braking force distribution represents a formidable challenge within the realm of riding skills. Therefore, the study on motorbike crashes has identified the improper application of front and rear brakes as a noteworthy pre-impact factor [5], [8]. Furthermore, in perilous circumstances, bikers often transition from a standard riding style to an unpredictable sequence of behaviours encompassing braking, handling, or a combination of both [9].

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In the domain of motorbike dynamics, the distribution of braking force undergoes variability contingent upon factors such as deceleration intensity, the Center of gravity (CG) positioning, and accounting for both biker load and pillion load [10]–[13]. The motorbike experiences substantial enhancements in braking effectiveness and stability when braking force is distributed appropriately. Maximizing the efficacy of braking can be achieved by maintaining the optimal distribution of brake force throughout the braking process. As deceleration escalates, weight transfer towards the front causes the distribution of brake force to become non-linear [14], [15]. Hence, this study aims to investigate how the deceleration rate and load from biker and pillion collectively influence the identification of the optimal distribution of braking force on a motorbike.

2.0 METHODOLOGY

Altair HyperStudy was used in this study to facilitate the design exploration. It was executed by establishing the setup model, design of experiment (DOE), and approximation, as shown in Fig. 1. The analytical analysis of the motorbike's brake force distribution leveraged the computational capabilities embedded within Altair HyperStudy's internal solver. A mathematical model was devised to assess motorbike braking-force efficacy. The equation was derived from the motorbike's braking motion equation. Integrating an algorithm into the template file governs the relationship between the braking force and the motorbike's CG, according to the standards set by the Altair HyperStudy. This document encompasses an algorithmic representation of the solver's input configuration and adjustable parameters. The file encompassing parameter statements is commonly known as a setup model and is processed using a Templex solver. Templex can be described as the parameterization tool used to modify the parameter designs in the template file and solve the output response for each Altair HyperStudy iteration. Establishing the setup model, the subsequent step involved selecting design factors specific to this particular model. The designation of biker and passenger masses as parameter designs in this study is elaborated in Table 1. For the biker mass (*R*), three levels of mass were assigned in this study, which include 50 kg, 75 kg, and 100 kg. The selected levels reflect a range of biker mass based on anthropometric data [16]–[18]. Meanwhile, the passenger mass (*P*) was assigned to level 1 of zero to represent the solo riding of the motorbike. Levels 2 and 3 were set at 75 kg and 100 kg, respectively, representing the maximum practical load. The range for deceleration (*a*) extends from level 1 of 0.1 g, representing the slow deceleration during braking, followed by 0.55 g, and level 3 at 1.0 g. These levels are selected to represent light, moderate, and emergency braking conditions [11], [12]. A comprehensive analysis has been undertaken to examine the effects of all parameters on the motorbike braking force distribution on both brake systems. Thus, the amount of front brake force denoted by $F_{B,\,F}$, and the rear brake force denoted by $F_{B,\,R}$, were solved by the algorithm based on Equation (1) for the front brake and Equation (2) for the rear brake. This work adopted the full factorial technique in the DOE setup. The execution was done using a 3^3 full factorial design (three parameters, three levels), which was employed and solved using a Templex solver. As a result, 27 iterations with various combinations of parameter designs were resolved using a Templex solver. Each iteration's output response was kept in a data source. Following the DOE study's conclusion, the computed response's run matrix was tallied. This study derived the motorbike specifications from previous research [19].

Table 1: Parameter design for full factorial analysis

Parameter	Unit	Level 1	Level 2	Level 3
Deceleration, a	g	0.1	0.55	1
Biker Mass, R	kg	50.0	75.00	100
Pillion Mass, P	kg	0.0	50.00	100

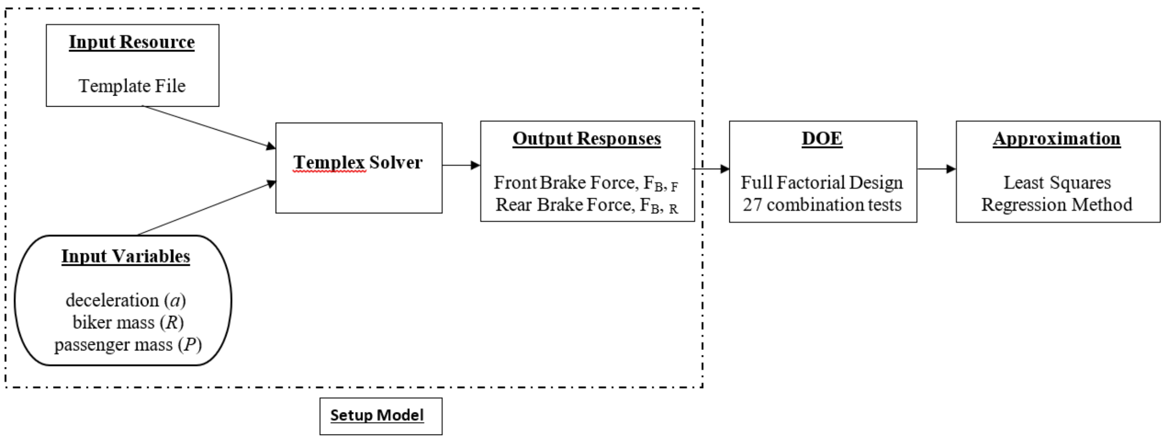


Figure 1. Block view of design exploration study by Altair HyperStudy

$$F_{B,F} = \frac{\mu W}{b}\left(l_2 + \frac{a}{g}h\right) \quad \text{(N)} \qquad (1)$$

$$F_{B,R} = \frac{\mu W}{b}\left(l_1 - \frac{a}{g}h\right) \quad \text{(N)} \qquad (2)$$

3.0 RESULTS AND DISCUSSION

An analysis of each parameter design's effect and interactions with front and rear brake forces is undertaken. Fig. 2 demonstrates the linearly positive impact of all the parameter designs on the front brake force, consistent with the trends observed in earlier studies on motorcycle braking dynamics [4], [11]. It shows that deceleration has the most extensive effect, as the mean difference is the largest at 1753.22 N. Subsequently, the passenger mass is depicted at 350.69 N, followed by the biker mass at 241.22 N. These values suggest that increasing parameter designs elevate the front brake force in the motorbike. In this study, an interaction was observed between deceleration and both the biker and the passenger, indicating that changes in deceleration affect the front brake force differently depending on whether there is a biker or passenger on the motorbike. However, no interaction was found between the biker and the passenger, suggesting that the biker's effect towards the front brake force remains constant regardless of the passenger's presence. Similarly, the passenger's presence consistently influences the front brake force, irrespective of whether the biker is present.

The combined effect of deceleration and passenger mass is critical in determining the front brake force of the motorbike. When the motorbike decelerated at a rate of 0.1 g, excluding the passenger's presence, the front wheel encountered 78.28 N of mean brake force. Meanwhile, the 100 kg passenger necessitated a mean front brake force of 96.25 N to slow down the motorbike until it was halted. When the motorbike decelerated at 1g without a passenger, the mean front brake force increased to 1454.33 N. Indeed, when subject to a maximum deceleration of 1g, accommodating a passenger weighing up to 100 kg, the motorbike necessitated a mean front brake force of 2226.64 N. Thus, the cumulative effect stemming from the deceleration and passenger interaction was manifested as 377.17 N. A subsequent implication of this interaction pertains to the deceleration and biker. When the motorbike experienced 0.1 g deceleration with a 50 kg biker, the mean front brake force was recorded at 76.11 N. This figure significantly increased to 98.42 N when the same deceleration was maintained, but with the biker's mass maxing out at 100 kg. The discernible escalation in braking force underscores the direct correlation between biker mass and braking requirements. Moreover, when the motorbike underwent a more rigorous deceleration of 1g, the front brake force rose substantially. Specifically, with a 50 kg biker, the force peaked at 1589.50 N, whereas under identical deceleration conditions but with a 100 kg biker, the force surged to 2091.47 N. This marked augmentation in braking force which accentuates the compounding effect of deceleration and biker mass on the braking system's demands. Thus, the cumulative impact of the deceleration rate and the mass of the biker obtained a significant force of 239.83 N. This underscores the intricate interplay between these parameters in determining the motorbike's braking force distribution [20].

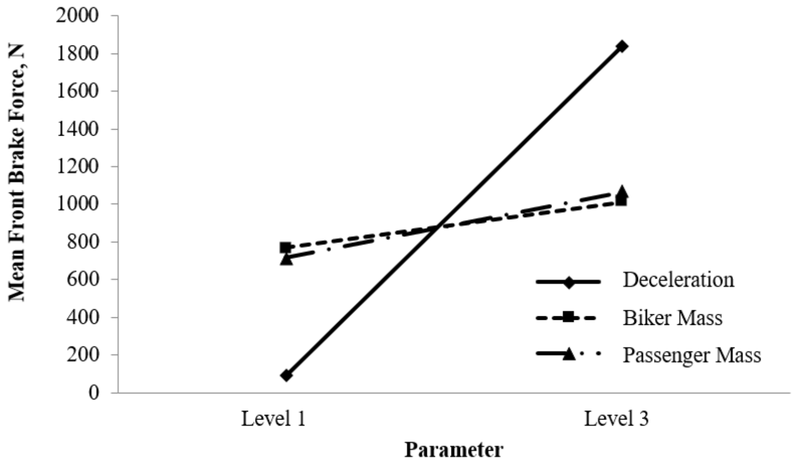


Figure 2. Effect of front brake force against parameter designs

Fig. 3 elucidates the linear impact of every parameter design on the rear brake force. This effect remains consistent with those observed for the influences on the front brake force. According to the depicted figure, it is discerned that all parameter designs exhibit a linearly positive influence on the rear brake force. The ongoing analysis revealed that deceleration maintained a considerable impact on rear braking, evidencing a mean variation of 214.77 N. Concurrently, the presence of a passenger yielded a discernible mean difference of 188.86 N on rear braking. Additionally, a mean difference of 28.56 N indicated the comparatively lesser impact of biker mass on the rear brake force. Through comparison of these values, it became apparent that the rear brake force of the motorbike escalated with the escalation of all parameter designs. Despite the linear impact of individual parameter designs, the study also scrutinized the interaction among all parameter designs on the rear brake force. From these data, it is evident that interaction exists between deceleration and biker mass, as well as between deceleration and passenger mass. However, there is a lack of discernible interaction between the bikers and the passengers. Notably, the influence of rear braking force persists consistently, irrespective of the presence or absence of either the biker or passenger. These interaction patterns are consistent with prior research [4], emphasizing the non-linear behaviour of braking force distribution under varying loading and deceleration conditions. At 0.1 g deceleration, the impact of biker mass on rear braking force was notably more pronounced compared to higher deceleration levels. Conversely, the impact of passenger to rear braking force demonstrated an inverse correlation, suggesting that as passenger mass increased, the effectiveness of the rear braking force decreased. The heightened impact observed at higher deceleration levels contributes to this phenomenon. Therefore, a calculated value of 64.28 N for the rear brake force was determined, emphasizing the pivotal role of the interplay between deceleration and passenger mass. Subsequently, the interaction between deceleration and biker mass, yielding a value of -19.10 N, underscored its secondary role in influencing the rear brake force.

A results matrix was calculated as the framework for articulating the brake force distribution model. The response surface, a mathematical representation of the brake force distribution model, was established across all parameter designs. This surface is a surrogate model for the braking force distribution, facilitating predictive capabilities for subsequent analysis and optimization endeavors. Ensuring the alignment between the response surface and the results matrix is crucial, warranting accuracy in the predictive model. Facilitated by Altair HyperStudy, the present inquiry utilized the Least Squares Regression (LSR) method to achieve this accuracy. To improve the precision of estimation, a study was undertaken on the value of R^2, which illustrates the extent of association between the measured and estimated data. According to its definition, R^2 is invariably smaller than 1.0. A value of R^2 that approaches 1.0 is commonly perceived as indicative of a superior level of accuracy in the fitness of a model. The selection of the squared regression model in the present analysis is justified by its superior ability to approximate fitting, as demonstrated by comparing the squared linear correlation coefficients for both responses. The R^2 demonstrates a strong correlation between the studied parameters, with values of 0.96 and 0.95. These values are in close proximity to unity. The front brake force model demonstrated a variability of 96% in the described data. The dataset showed that the rear brake force contributed about 95% of the observed variability.

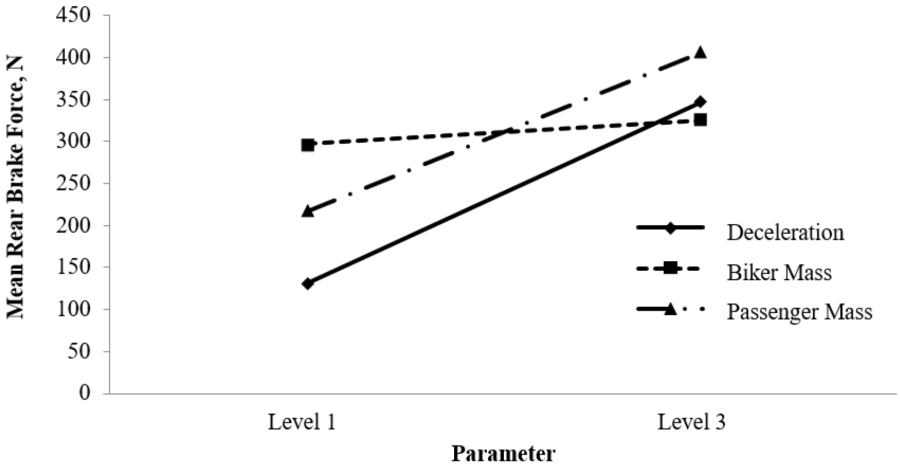


Figure 3. Effect of rear brake force against parameter designs

Additionally, the suitability of the proposed model regarding accessibility was evaluated using the analysis of variance (ANOVA) in identifying the parameter designs that significantly impacted both brake forces individually. The present analysis was assessed with a 95 % confidence level, aligning with a 0.05 significance level. A parameter design's statistical significance is accentuated when its F-value is elevated. Table 2 displays the outcomes of the ANOVA test on the front brake force, whereas Table 3 delineates the results for the rear brake force. According to the data from ANOVA, deceleration exhibited substantial statistical significance, with the highest value being 227.30, concerning the front brake force response. Subsequently, the passenger mass of 8.91 is considered along with the mass of the biker, which is 4.22. These results reflect those reported in the literature [3], [11], which consistently identifies deceleration and load as primary contributors of braking performance. A P-value below 0.05 within this model implies that the parameter design can be statistically significant. The findings presented in Table 2 signify that all parameter designs are statistically significant factors influencing the braking force on the front motorbike. It is evident from the obtained P-values, which are less than 0.05. Therefore, the proposed front brake force model offers a satisfactory explanation regarding the correlation of the parameter design with the response for front braking force. It accounts for approximately 96% of the observed variability in the dataset. Based on this model, only 4% of the total variability in the observed points was not captured. The model quantifies the unexplained variance, known as the sum of squares error, as 621043.60.

Table 3 presents the ANOVA test results and highlights the deceleration parameter (139.76) as significantly influential with the rear brake force. The following significant aspect concerns the mass of the passenger (45.59), whereas the relatively less important aspect is linked to the mass of the biker (1.04). According to the statistical analysis, the passenger mass and deceleration have a statistically significant impact on the rear brake force, as indicated by a P-value of less than 0.05 for both parameters. In contrast, the biker mass is deemed to have limited significance as a parameter because its P-value exceeds the 0.05 threshold. The rear brake force model provides an exhaustive explanation, accounting for 95% of the observed data variability. Just 5% of the total variance in the observed data remained unexplained. The sum of squares error, referring to the unexplained variance in the model, is measured as 35207.62. The regression equations are developed to elucidate the relationship among the significant terms identified through the ANOVA. The regression equations delineating the front brake force are encapsulated in Equation 3. This equation is adept at predicting the magnitude of the front brake force applied by the motorbike, albeit under specific analysis conditions. Notwithstanding its proficiency in forecasting the front brake force, the regression model also yields Equation 4, which is instrumental in estimating the rear brake force. This dual capability of the regression model highlights its comprehensive utility, enabling precise predictions of both front and rear brake forces, thereby enhancing the overall performance of the motorbike's brake across varied parameter designs.

Table 2: Parameter design for full factorial analysis

Parameters	Degree of Freedom (DOF)	Sum of Squares	Mean Squares	F-value	p-value
a	2	1.41×10^{7}	7058252.00	227.30	1.77×10^{-14}
R	2	261839.60	130919.80	4.22	0.029661
P	2	553430.90	276715.50	8.91	0.001709
Error	20	621043.60	31052.18		
Total	26	1.56×10^{7}			

Table 3: Parameter design for full factorial analysis

Parameters	Degree of Freedom (DOF)	Sum of Squares	Mean Squares	F-value	p-value
a	2	492071.80	246035.90	139.76	1.76×10^{-12}
R	2	3669.65	1834.82	1.04	0.37103
P	2	160503.70	80251.83	45.59	3.55×10^{-8}
Error	20	35207.62	1760.381		
Total	26	691452.80			

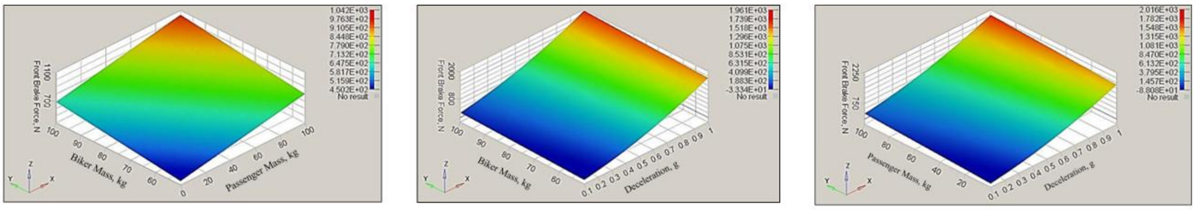
$$F_{B,F} = -537.18 + 765.13a + 4.82R + 3.51P + 1075.35a^2 - 0.000000942R^2 - 0.000000236P^2, \quad \text{(N)} \qquad (3)$$

$$F_{B,R} = -137.26 + 1421.52a + 0.57R + 1.89P - 1075.35a^2 + 0.0000000711R^2 + 0.0000000178P^2, \quad \text{(N)} \qquad (4)$$

where
$F_{B,F}$ for Front Brake Force, in the unit of Newton (N)
$F_{B,R}$ for Rear Brake Force, in the unit of Newton (N)
a for deceleration, in the unit of g
R for biker mass, in the unit of Kilogram (kg)
C for passenger mass, in the unit of Kilogram (kg)

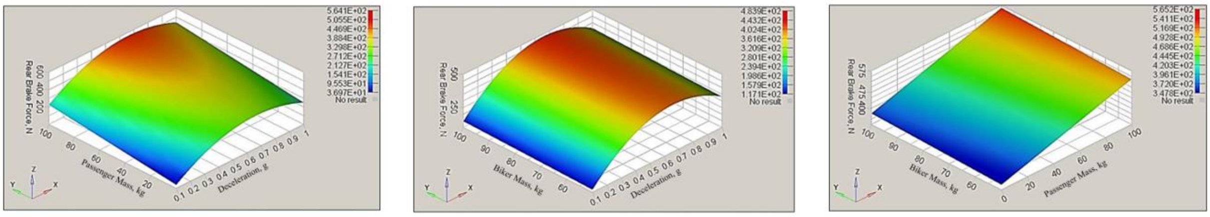
The correlation between two parameter designs and the brake force is depicted by the response surface illustrated in Figs. 4 and 5. The utilization of 3D surface plots enables a more comprehensive grasp of how all parameter designs impact the response of brake force. Furthermore, these plots assist in identifying the most favorable distribution of brake force for motorbikes. In this analysis, the response surfaces were graphed to depict the interaction between two parameter designs, maintaining all other parameters at moderate levels. Utilizing the Altair HyperStudy, the figures within this study were meticulously generated, incorporating the optimization procedure. Fig. 4, specifically, illustrates the front brake force response at 0.55 g through a surface plot, vividly capturing the fluctuations in this response across varying masses of the biker and passenger. The combined effect of both masses positively influenced the front braking force of the motorbike. The front brake force increased from 450 N to 691 N as the biker mass increased from 50 kg to 100 kg. The maximum front brake force was 1042 N when the motorbike carried a total load of 100 kg for the biker and an additional 100 kg for the passenger. The observed increases can be readily elucidated by considering the increment of front static load resulting from the augmented masses of the biker and the passenger on the motorbike. The front brake force exhibited a positive correlation with the magnitude of deceleration. Bringing the motorbike to a halt with a deceleration of 1 g required a biker weighing 100 kg to apply a front brake force of 1961 N. The influence of biker mass on the front brake force exhibited a slight augmentation, irrespective of the deceleration. Therefore, it can be inferred that deceleration exerts the most significant impact on the magnitude of the front brake force. An increased deceleration is indicative of a reduced stopping time. Hence, an additional front braking force is needed for the motorbike to stop, regardless of the combined weight of the passenger and biker.

The quadratic relationship for the rear brake force with deceleration while carrying the biker and the passenger can be observed in Fig. 5. The motorbike exhibited its highest rear brake force during deceleration at an approximate rate of 0.7 g. The primary cause of the nonlinearity observed in the response surface can be attributed to the effect of load transfer that occurs while the motorbike is braking. The static load initially exerted on the rear is transferred to the front during braking. This reduces the rear static load, thereby contributing to the non-linear distribution. The rear brake force is influenced by both the pillion and biker, similar to their impact on the front brake force, which has been demonstrated. The force applied to the rear brake is augmented in response to an increase in the mass of the passenger. Nevertheless, as the biker mass increases, there is a slight increase in the force exerted by the rear brake. The observed phenomenon can be attributed to the increase in rear static load resulting from the presence of both a biker and a passenger on the motorbike. The added masses impact the CG transformation and consequently affect the static load distribution on both brakes. According to the aforementioned analysis, all parameter designs significantly affect brake force distribution. Nevertheless, the predominant factor influencing both motorbike braking forces is derived from deceleration. Hence, the primary consideration in determining the optimal brake force condition lies in assessing the impact of deceleration on the dissemination of braking force while also considering the average influence of both the biker's and passenger's mass.



(a) (b) (c)

Figure 4. Front Brake Force Response Surface Versus (a) Biker Mass and Passenger Mass, (b) Deceleration and Biker Mass, and (c) Deceleration and Passenger Mass Input Parameter



(a) (b) (c)

Figure 5. Rear Brake Force Response Surface Versus (a) Deceleration and Passenger Mass, (b) Deceleration and Biker Mass, and (c) Passenger Mass and Biker Mass Input Parameter

During the braking event, the force applied to the front brake initiates a load transfer. The application of additional front brake force must accommodate the increased burden. Therefore, increasing deceleration intensity leads to a corresponding increase in the brake force applied to the front. In addition to the front brake management, an appropriate amount of force must be applied to the rear brake. The necessity of employing and controlling the rear brake arises in maintaining the motorbike’s stability during braking. Hence, it is crucial to ascertain the optimal braking force distribution on both wheels to effectively utilize the tires and the road surface friction, thereby maximizing the braking performance. This exploration demonstrated a direct relationship between the extent of deceleration and the corresponding augmentation in front brake force. The study revealed a non-linear relationship between deceleration and the ideal front brake force. As the rate of deceleration progressively rose, reaching a peak of 1 g, the corresponding optimal magnitude of the front brake force also increased, ultimately reaching its maximum value of 1841 N. Conversely, the ideal rear brake force curve exhibited a nearly linear growth during the initial phase of deceleration. The rate of increase exhibited an approximate growth of 75% prior to reaching the maximum value in the rear brake force curve. This peak was observed during deceleration within the 0.4 g to 0.7 g range. The maximum rear brake force observed was 465 N at 0.69 g deceleration. The rear brake force at its optimal level demonstrated a consistent decline, decreasing by 21% beyond a deceleration of 0.7 g. The associated optimal state was achieved as the deceleration rate gradually increased, reaching a maximum of 1 g. The optimal rear brake force decreased at a constant rate of 21% after a deceleration of 0.7 g.

4.0 CONCLUSION

This study analysed the effects of various parameter designs on a motorbike's front and rear brake forces, including deceleration, biker mass, and passenger mass. The results revealed a significant positive linear relationship between these parameters and brake forces, with deceleration emerging as the most influential factor. A deceleration increase resulted in a mean front brake force increase of up to 1753.22 N, while biker and pillion masses contributed an increase of 241.22 N and 350.69 N, respectively. Interaction analysis showed that deceleration combined with a biker or passenger mass significantly impacted the front brake force. Specifically, the interaction between deceleration and passenger mass-produced a mean front brake force of 2226.64 N at 1g deceleration with a 100 kg passenger. Similarly, deceleration combined with biker mass resulted in a front brake force of 2091.47 N under the same conditions. For the rear brake force, the combined influence of deceleration and passenger mass yielded a force of 64.28 N. Meanwhile, the interaction with biker mass showed a less significant impact, indicating greater sensitivity of rear brake force to passenger mass at higher decelerations. The response surface methodology and LSR model accurately predicted brake force distribution, with R^2 values of 0.96 for the front brake force and 0.95 for the rear brake force. ANOVA confirmed the statistical significance of deceleration, passenger mass, and biker mass on brake forces, particularly highlighting deceleration as the most critical parameter. The study concludes that optimal brake force distribution for motorbikes depends primarily on deceleration. The front brake force increases markedly with deceleration, necessitating higher brake forces to ensure effective stopping power and motorbike stability. Conversely, rear brake force shows a non-linear response, peaking at around 0.7 g deceleration before declining. These findings emphasize the importance of balancing front and rear brake forces to maximize braking efficiency and safety. Synchronized braking is essential to achieve this balance, with the Concurrent Brake Actuator (CBA) being effective in controlling the needed distribution to maintain the requisite non-linear brake force distribution.

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AUTHORS CONTRIBUTION
M. Hisyam Basri: Conceptualisation, methodology, formal analysis, investigation, and writing-original draft;
N.I. Ismail: Conceptualisation, methodology, and formal analysis;
Arif Pahmi: Conceptualisation, formal analysis, and validation;
R. Rabilah: Conceptualisation, writing-review, and editing, and validation;
Hazim Sharudin: Conceptualisation, and writing-review and editing.

DECLARATION OF COMPETING OF INTEREST
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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