Performance Gains Of Load Sensing Brake Force Distribution In Motorcycles

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Abstract: Commercial motorcycles and scooters incorporate independent circuits for front and rear brake actuation, thus precluding load-dependent brake force distribution. In all cases of manual brake force modulation between the front and rear wheels, there is poor compensation for the changes in wheel loads on the account of longitudinal weight transfer, thus making it challenging to provide an adequate braking force to each wheel. The ration in which the braking force should be distributed between the front and the rear wheels is dependent on the motorcycle geometry, weight distribution, mechanical sizing of braking system components, and is a variable based on the instantaneous deceleration. This connotes that a fixed bias of front and rear braking forces can be optimized only for a narrow range of motorcycle's deceleration. Maximum braking performance occurs just prior to wheel lockup, as a sliding tire provides less grip than a rolling tire. This is also the scenario when both the tires are doing the maximum work in decelerating the motorcycle. Therefore an optimal brake force distribution is one that locks both wheels at the same instant. In practice, however, a rider would avoid a front wheel lock-up as it would make the motorcycle challenging to steer. In theory an apt distribution of the braking forces between the front and rear wheels maximizes the overall braking efficiency of the motorcycle whilst reducing its stopping distance. This paper examines plausible performance gains of load sensing brake force distribution in a motorcycle.

Index Terms: Brake Force Distribution, Motorcycle Braking, Stopping Distance, Vehicle Dynamics.

1 Introduction

Various factors influence the overall performance of a motorcycle's braking system, some of these factors include the master cylinder diameter, loaded radius of the tires, and brake pad material. Moreover, the braking system must comply with regulatory requirements regarding braking distance and the amount of force required to slow down the motorcycle.

A dominant decisive factor determining the overall braking efficiency is the distribution of brake force across the front and the rear wheels. Brake biasing is a method of regulating the braking forces distributed across the front and the rear wheels; indicated as a percentage, it is a representation of the magnitude of braking force at each end of the motorcycle. For example; 70/30% means that the front brake is expected to produce 70% of the total braking force. This is an adjustment of the relative amount of hydraulic pressure applied to the front versus the rear brake calipers. As a motorcycle decelerates, weight is transferred to the front tire, thus improving its grip, whilst decreasing the grip available at the rear tire. In addition, the size of the front and rear brake rotors, pads, and piston area are often different requiring different amounts of hydraulic pressure to generate the same magnitude of braking force.

Manual brake force modulation between the front and the rear wheel using independent brake circuits has a major drawback of not providing optimum braking performance in all braking scenarios. In theory, load sensing brake force distribution eliminates the dependency of the braking system on rigid constraints and rider judgement, thus facilitating the system to account for loading conditions and dynamic weight transfer at any dynamic braking condition and to adjust the relative hydraulic pressure applied to the front and rear brake calipers in order to maximize overall braking efficiency of the motorcycle and reduce its stopping distance.

2 Influence of Dynamic Weight Transfer

In the condition of zero acceleration, a motorcycle will have a fixed weight distribution, resulting in the two contact patches of the motorcycle suspending a fixed percentage of the total weight.

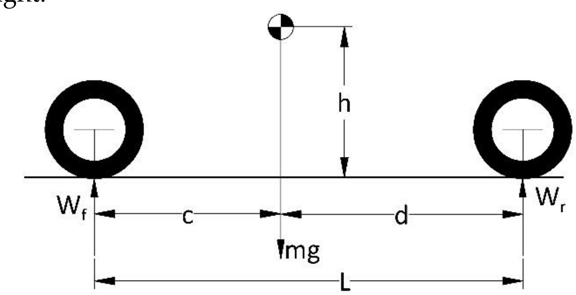

Figure 1: Side-view model of a motorcycle.

Analyzing the motorcycle and rider system in a lateral plane, as represented in Fig. 1, the sum of moments about the front and rear wheels must be zero.

$$\sum M_f = 0 = W_r(c+d) - mgc \quad (1)$$
$$\sum M_r = 0 = mgd - W_f(c+d) \quad (2)$$

Thus,

$$W_f = \frac{mg\times d}{(c+d)} = \frac{W\times d}{L} \quad (3)$$

$$W_r = \frac{mg\times c}{(c+d)} = \frac{W\times c}{L} \quad (4)$$

Where,

m = Mass of the system
W = Weight of the system
c = Longitudinal distance of front wheel from system CG
d = Longitudinal distance of rear wheel from system CG
L = Wheelbase of the motorcycle
W_f = Static front wheel load (with rider)
W_r= Static rear wheel load (with rider)

The normal reaction loads at each wheel can be determined using weighing scales placed at both the tire-road contact patches of the motorcycle and conversely the longitudinal position of the system's centre of gravity (CG) can be calculated as follows;

$$c = \frac{W_r}{W} \times L \tag{5}$$

$$d = \frac{W_f}{W} \times L \tag{6}$$

Whenever a motorcycle decelerates, the effective normal loads reacted at the contact patches will change. While the total normal load remains constant, the front wheel load during deceleration will increase and the rear wheel load will decrease by the same magnitude.

This dynamic weight transfer in deceleration can be computed with reference to the dynamic free-body diagram shown in Figure 2.

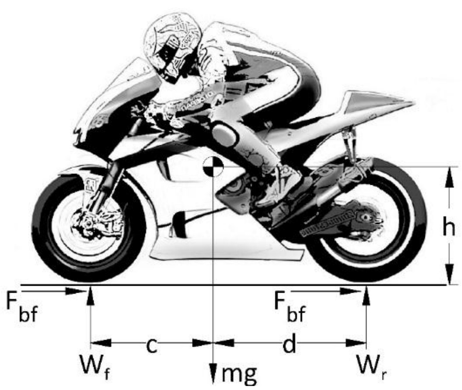

Figure 2. Free body diagram of a motorcycle under braking.

The braking forces generated at the front and the rear tires are represented by F_{bf} and F_{br} respectively. The height of center of gravity of the system from the ground is denoted by h.

Assuming that the motorcycle is established under steady-state braking with deceleration of d_x, application of Newton's law yields the following equations;

$$\sum F_x = md_x = F_{bf} + F_{br} \tag{7}$$

$$\begin{aligned} \sum F_y &= 0 = W_f' + W_r' - mg \\ &\Longrightarrow W_r' = mg - W_f' \end{aligned} \tag{8}$$

Where,
W_f' = Dynamic load on the front wheel
W_r' = Dynamic load on the rear wheel

$$\begin{aligned} \sum M_{CG} = 0 &= h(F_{bf} + F_{br}) + W_r(d) - W_r(c) \\ &= ma_x h + W_r(d) - W_f(c) \end{aligned} \tag{9}$$

These equations can be used to compute the instantaneous load on each wheel in the event of braking.

$$W_f' = \frac{mgd}{L} + \frac{md_x h}{L} \tag{10}$$

$$W_r' = \frac{mgc}{L} - \frac{md_x h}{L} \tag{11}$$

The first term of the equations represent the static wheel loads, as obtained from equation (3) and equation (4). Defining the second term of the equations as dynamic weight transfer (W_d), equations (10) and (11) can be rephrased as;

$$W_f' = W_f + W_d \tag{12}$$

$$W_r' = W_r - W_d \tag{13}$$

Therefore, the dynamic weight transfer in the event of braking can be expressed as;

$$W_d = \frac{m \times d_x \times h}{L} \tag{14}$$

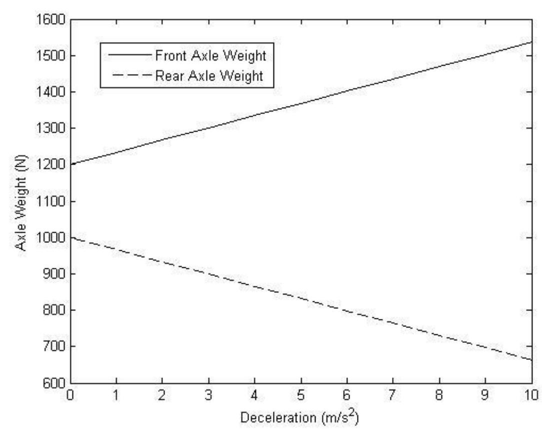

Figure 3. Weight transfer as a function of deceleration.

Since the maximum possible braking force that a tire can generate is equal to the coefficient of friction at the tire-road interface times the normal load on the tire, the front tire will have an increased capacity to provide braking force under decelerating. Given that the front tire furnishes the majority of the braking force, implementation a system devised to apportion the braking force between the front and rear brake calipers such that more brake pressure is applied to the front brake caliper, would enhance the braking performance of a motorcycle. [1]

3 Distribution of Braking Force

Maximum braking performance occurs just before wheel lock-up, as a sliding tire has less grip than a rolling tire. Since the maximum braking performance will be delivered when both the tires are doing the maximum work associated with braking, an ideal brake force distribution is one that locks the front and the rear wheels at the same instant. Assuming that the same coefficient of friction exists at both contact patches, the maximum braking force that can be achieved at each tire is directly proportional to the load suspended by the tire.

Therefore, to achieve the maximum braking performance, the braking force distribution between the front and the rear wheels should be proportional to the instantaneous wheel loads in the event of braking. In other words, whilst decelerating, if the front wheel suspends 60% of the weight and the rear wheel suspends the remaining 40% of the weight, achieving maximum braking performance would require 60% of the total braking force to be provided by the front tire and 40% by the rear tire. This distribution of braking forces, which can be designed into the system, is a good measure towards achieving simultaneous wheel lock-up at both the wheels.

3.1 Safety Considerations

Lock-up of any or both wheels has significant handling consequences. If the rear wheel locks-up first, the motorcycle will lose its straight line stability. In the event of a rear wheel lock-up, the rear contact patch cannot resist any lateral movement. Slight forces, because of side winds or other factors, will cause the rear wheel to move laterally. This will result in a yawing moment of inertia force about the yaw centre to be developed, causing further lateral motion of the rear wheel.

On the other hand, if the lock-up starts at the front wheel, directional control of the motorcycle is lost. The rider will not be able to steer the motorcycle as the stationary contact patch is unable to generate any cornering forces.

Although front wheel lock-up does not cause the kind of directional instability noticed with rear wheel lock-up, it puts the rider at the risk of tip-over without the ability to steer the motorcycle.

When directional stability is lost in the case of a rear wheel lock-up, the rider can regain it by applying corrective steer input to the handlebar. However, in the event of a front wheel lock-up, it is extremely difficult for the rider to modulate brake pressure in order to prevent complete tip-over of the motorcycle or regain directional control.

Because of these safety considerations, brake force distribution requirement will call for rear wheel lock-up to occur ahead of front wheel lock-up. Although this will not permit the attainment of the same level of braking performance as that with simultaneous wheel lock-up, it is worthwhile to design the braking system such that the rear wheel lock-up occurs ahead of front wheel lock-up. [2]

3.2 Balancing of Braking Force

Theoretically, the maximum braking force that a particular tire can generate is equal to the peak coefficient of friction at the tire-road interface multiplied by the amount of weight suspended by it.

During braking, dynamic weight transfer from the rear to the front wheel occurs such that the load on the front wheel is the wheel's static load plus dynamic weight transfer contributions. Thus, for a longitudinal deceleration dx ;

$$F_{bf}^{max} = \mu_p W_f' = \mu_p (W_f + W_d) = \mu_p \left(W_f + \frac{m \times d_x \times h}{L}\right) \quad (15)$$

$$F_{br}^{max} = \mu_p W_r' = \mu_p (W_r - W_d) = \mu_p \left(W_r - \frac{m \times d_x \times h}{L}\right) \quad (16)$$

Where,

F_{bf}^{max} = Maximum braking force of the front wheel
F_{br}^{max} = Maximum braking force of the rear wheel
μ_p = Peak coefficient of friction at tire-road interface

Therefore, the maximum braking force is dependent on the deceleration, varying differently at each wheel.

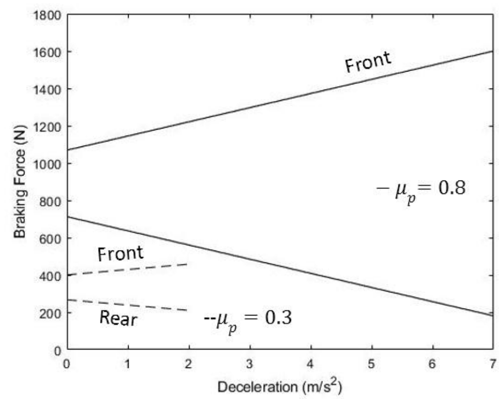

Figure 4. Maximum braking forces of a tire as a function of deceleration.

An explicit solution for the maximum braking force at each tire can be obtained by recognizing that the deceleration is a function of the total braking force imposed on the vehicle. To solve for F_{bf}^{max}, the following relationships can be used;

$$d_x = \left[\frac{F_{bf}^{max} + F_{br}}{m}\right] \quad (17)$$

and for F_{br}^{max};

$$d_x = \left[\frac{F_{br}^{max} + F_{bf}}{m}\right] \quad (18)$$

Substituting into equation (17) into equation (15) and equation (18) into equation (16) yields the following equations for the maximum braking force on each wheel;

$$F_{bf}^{max} = \frac{\mu_p\left[W_f + \frac{h}{L} F_{br}\right]}{1 - \mu_p \frac{h}{L}} \quad (19)$$

$$F_{br}^{max} = \frac{\mu_p\left[W_r - \frac{h}{L} F_{bf}\right]}{1 + \mu_p \frac{h}{L}} \quad (20)$$

Thus the maximum braking force on the front wheel is dependent on that present on the rear wheel through the deceleration and associated dynamic weight transfer resulting from the rear brake action. Conversely, the same effect is evident on the rear wheel. [3]

4 CONVENTIONAL APPROACH TO BRAKING ON A MOTORCYCLE

Most of the braking force of standard motorcycle comes from the front wheel. If the brakes themselves are strong enough, the rear wheel is easy to skid, while the front wheel often can generate enough stopping force to flip the rider and bike over the front wheel. This is called a stoppie if the rear wheel is lifted but the bike does not flip, or an endo if the motorcycle flips. On long or low motorcycles, however, such as cruiser motorcycles, the front tire will skid instead, possibly causing a loss of balance. [4]

4.1 Braking at the Front Wheel

The limiting factors on the maximum deceleration in front wheel braking are as following:

- Limiting value of static friction between the tire and the ground, often between 0.5 and 0.8 for rubber on dry asphalt [5]
- Kinetic friction between the brake pads and the rim/rotor
- Pitching or looping (of motorcycle and rider) over the front wheel.

In the event of a front wheel braking, the maximum braking force that can be generated at the front tire will be equal to the instantaneous load suspended by the contact patch multiplied by the peak coefficient of friction.

$$F_{bf}^{max} = \mu_p W_f' \qquad \text{(From equation 15)}$$

Any braking force at the rear wheel will not be present. The maximum deceleration in this case can be found using equation (17).

$$d_x = \left[\frac{F_{bf}^{max} + F_{br}}{m}\right] \qquad \text{(From equation 17)}$$

For the condition of rear wheel braking, equation (17) can be rewritten as;

$$d_f^{max} = \frac{F_{bf}^{max}}{m} \tag{21}$$

In the equation above d_x is replaced by d_f to indicate that the equation is valid only when the front brake alone is applied. Using equation (15), we get,

$$d_f^{max} = \frac{\mu_p W_f'}{m} \tag{22}$$

Using equation (10), the above equation can be rearranged as;

$$d_f^{max} = \frac{\mu_p}{m}\left[\frac{mgd}{(c+d)} + \frac{md_f h}{(c+d)}\right] \tag{23}$$

The equation can be solved directly for maximum deceleration as;

$$d_f^{max} = g\frac{\mu_p\left(\frac{d}{L}\right)}{1-\mu_p\left(\frac{h}{L}\right)} \tag{24}$$

4.2 Braking at the Rear Wheel

Because of the decrease in rear wheel load under deceleration, most of the braking action of a motorcycle is generated by the front tire. There are, however, situations that may warrant rear wheel braking.

- Slippery surfaces or bumpy surfaces. Under front wheel braking, the lower coefficient of friction may cause the front wheel to skid which often results in a loss of balance.
- Front brake failure.
- To deliberately induce a rear wheel skid to achieve a small turn radius.

A similar treatment can be made when the brake is applied only to the rear wheel. In this case, any braking force on the front wheel will not be present, and the braking force on the rear wheel is given by the following equation;

$$F_{br}^{max} = \mu_p W_r' \qquad \text{(Using equation 16)}$$

An equation for the maximum deceleration when under rear wheel braking can be developed as;

$$d_r^{max} = g\frac{\mu_p\left(\frac{c}{L}\right)}{1+\mu_p\left(\frac{h}{L}\right)} \tag{25}$$

4.3 Braking at Both Wheels

Assuming that the braking system is biased to distribute the braking forces such that a certain ratio (K_f) of the total braking force (F_b^{total}) is directed to the front brake. The remainder that goes to the rear brake and is $(1 - K_f)$ of the total braking force.

$$F_{bf} = K_f F_b^{total} \tag{26}$$

$$F_{br} = (1 - K_f) F_b^{total} \tag{27}$$

Alternatively,

$$F_{bf} = \frac{K_f}{1-K_f} F_{br} \tag{28}$$

$$F_{br} = \frac{1-K_f}{K_f} F_{bf} \tag{29}$$

Consider the free body diagram of the motorcycle under direct braking forces F_{bf} at the front wheel and F_{br} at the rear wheel as depicted in Figure 2.

Neglecting the retarding effects of aerodynamic force, grade, and rolling resistance, the total braking force can be expressed as;

$$F_b^{total} = F_{bf} + F_{br} \tag{30}$$

4.3.1 Front Wheel Lock-up

Under front wheel lock-up, $F_{bf} = \mu_p W_f'$. Substituting this into equation (7) yields;

$$md_x = \mu_p W_f' + F_{br} \tag{31}$$

$$\Rightarrow md_f = F_{bf} + \frac{1-K_f}{K_f} F_{bf} \qquad \text{(Using equation 29)}$$

Deceleration (d_x) is denoted with subscript f to indicate that the deceleration obtained using the equation is valid only when the front wheel is locked-up. Using equation (10);

$$\Rightarrow md_f = F_{bf}\left(\frac{1}{K_f}\right) = \mu_p W_f'\left(\frac{1}{K_f}\right)$$
$$= \mu_p\left(\frac{mgd}{c+d} + \frac{md_f h}{c+d}\right)\left(\frac{1}{K_f}\right) \tag{32}$$

Rearranging for d_f yields;

$$d_f = g\frac{\mu_p\left(1+\frac{1-K_f}{K_f}\right)\left(\frac{d}{L}\right)}{\left[1-\mu_p\left(1+\frac{1-K_f}{K_f}\right)\left(\frac{h}{L}\right)\right]} \tag{33}$$

4.3.2 Rear Wheel Lock-up

Under rear lock-up, $F_{br} = \mu_p W_r'$. Substituting this and equation (11) into equation (7) yields;

$$md_x = F_{bf} + F_{br} \qquad \text{(From equation 7)}$$
$$\Rightarrow md_r = \frac{K_f}{1-K_f}F_{br} + F_{br} = F_{br}\left(\frac{1}{1-K_f}\right)$$
$$= \mu_p W_r'\left(\frac{1}{1-K_f}\right) = \mu_p\left(\frac{mgc}{c+d} - \frac{md_r h}{c+d}\right)\left(\frac{1}{1-K_f}\right) \tag{34}$$

Deceleration (d_x) is denoted with subscript r to indicate that the deceleration obtained using the equation is valid only when the rear wheel is locked-up.

$$\Rightarrow md_r = \mu_p\left(\frac{mgc}{c+d} - \frac{md_r h}{c+d}\right)\left(1 + \frac{K_f}{1-K_f}\right) \tag{35}$$

Rearranging for d_r yields;

$$d_r = g\frac{\mu_p\left(1+\frac{K_f}{1-K_f}\right)\left(\frac{c}{L}\right)}{\left[1+\mu_p\left(1+\frac{K_f}{1-K_f}\right)\left(\frac{h}{L}\right)\right]} \tag{36}$$

4.4 Braking Technique

Expert opinion varies from "use both levers equally at first"[5] to "the fastest that you can stop any motorcycle of normal wheelbase is to apply the front brake so hard that the rear wheel is just about to lift off the ground,"[6] depending on road conditions, rider skill level, and desired fraction of maximum possible deceleration.

In all cases manual brake force modulation among the front and rear wheels, there is poor compensation for the changes in wheel loads on the account of dynamic weight transfer in the longitudinal axis of the motorcycle that occurs during braking.

5 LOAD SENSING BRAKE FORCE DISTRIBUTION

A statically biased or non-biased brake setup has a major drawback of not providing optimum performance in all braking scenarios. The static bias is set for a particular situation based on pre-established constraints. Manual brake force modulation between the front and the rear wheel will provide optimum brake force distribution momentarily.

Load sensing brake force distribution will allow the braking system to provide brake force to each wheel based on instantaneous vertical load supported by the wheels, a parameter which is a variable because of the ever-present phenomena of dynamic weight transfer.

5.1 Achieving Optimal Braking Performance

Maximum braking performance is achieved when a maximum braking force is obtained. The maximum braking force is achieved when both the front and rear wheels approach lock-up at the same time. To achieve this, the braking force at each wheel should be proportional to the instantaneous axle load. There are two major factors affect the brake force distribution. The influence of these factors are described as follows:

- First, the loading condition of the motorcycle (fully loaded versus lightly loaded) will cause movement of the centre of gravity of the system, thereby causing a change in the static weight distribution of the motorcycle. This means that a certain optimal brake force distribution for a specific loading condition may not be the same as that for another loading condition.

- Second, depending on the motorcycle's geometry and it's mass distribution, the vertical loads acting at each wheel will change as a function of deceleration during braking, thus altering the peak traction available at each contact patch.

Improper brake force distribution will cause one end or the other to lock-up first resulting in loss of cornering traction at that end. Proper brake balance is a function of loads on the wheels, which is, in turn a function of deceleration. [7]

5.2 Mathematical Modeling

For the purposed of statistically evaluating the braking performance of a motorcycle with variation in its front brake force distribution factor, weight and dimensional specifications of Repsol Honda MotoGP bike 2018 RV213V [8] is used for mathematical modeling.

- Weight of motorcycle (W_m) = 157 kg.f
- Weight of rider (W_r) = 70 kg.f
- Total weight of the system (W) = 227 kg.f ($W_m + W_r$)
- Front weight bias (W_f/W)= 0.6
- Wheelbase (L) = 1435 mm

- Height of centre of gravity (h) = 600 mm
- Peak coefficient of friction at tire-road interface in dry road condition (μ_p) = 0.8

Peak coefficient of friction at tire-road interface in wet road condition (μ_p) = 0.3

5.3 Calculations

5.3.1 Static Weight Distribution

In the condition of zero acceleration, a motorcycle will have a fixed weight distribution which results in both contact patches suspending a fixed percentage of the total weight.

Weight on front wheel =
Weight of the system $\times$ Front weight bias

$$W_f = W \times \frac{W_f}{W} \tag{37}$$

$$\therefore W_f = 227\text{kg} \times 9.81\text{m/s}^2 \times 0.6 = 1336.122\text{ N}$$

Similarly,

Weight on rear wheel =
Weight of the system $\times$ Rear weight bias

$$W_r = W \times \left(1 - \frac{W_f}{W}\right) \tag{38}$$

$$\therefore W_r = 227\text{ kg} \times 9.81\text{ m/s}^2 \times (1 - 0.6) = 890.748\text{ N}$$

Based on the static weight distribution, the longitudinal position of the motorcycle's center of gravity can be computed as a function of its geometry;

$$c = \frac{W_r}{W} \times L \qquad \text{(From equation 5)}$$

$$\therefore\ c = \frac{890.748\text{ N}}{227\text{ kg} \times 9.81\text{m/s}^2} \times 1435\text{ mm} = 574\text{ mm}$$

And,

$$d = \frac{W_f}{W} \times L \qquad \text{(From equation 6)}$$

$$\therefore\ d = \frac{1336.122\text{ N}}{227\text{ kg} \times 9.81\text{m/s}^2} \times 1435\text{ mm} = 861\text{ mm}$$

5.3.2 Dynamic Impact on the Motorcycle

Whenever a motorcycle decelerates, the effective normal forces reacted at both contact patches will change. As the following equation demonstrates, the magnitude of this weight transfer is a function of deceleration and motorcycle's geometry:

$$W_d = \frac{m \times d_x \times h}{L} \qquad \text{(From equation 14)}$$

The upper limit of deceleration for a motorcycle is determined by the peak coefficient of friction available at the tire-road interface and is given by;

$$d_x^{max} = \mu_p \times g \tag{39}$$

For the motorcycle-rider system in consideration, the maximum attainable deceleration is;

$$d_x^{max} = 0.8\ \times 9.81\text{m/s}^2 = 7.848\text{ m/s}^2$$

Thus, all calculations for dry road conditions are performed for a maximum deceleration of 7.848 m/s^2 .

When the motorcycle decelerates at 7.848 m/s^2, the magnitude of weight transfer can be calculated using equation (14).

$$W_d = \frac{227\text{ kg} \times 7.848\text{ m/s}^2 \times 600\text{mm}}{1435\text{ mm}} = 744.876\text{ N}$$

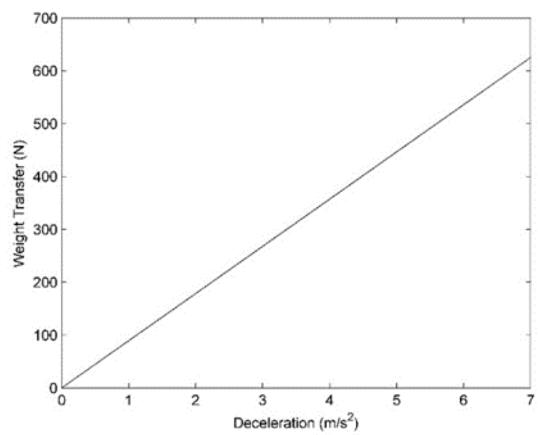

Figure 5. Weight transfer as a function of deceleration.

In order account for the instantaneous wheel loads in an event of braking, the weight transferred is added to the front wheel static load and subtracted from the rear wheel static load.

$$W_f' = W_f + W_d \qquad \text{(From equation 12)}$$

$$\therefore W_f' = 1336.122\text{ N} + 744.876\text{ N} = 2080.998\text{ N}$$

Similarly,

$$W_r' = W_r - W_d \qquad \text{(From equation 13)}$$

$$\therefore W_r' = 890.748\text{ N} - 744.876\text{ N} = 145.872\text{ N}$$

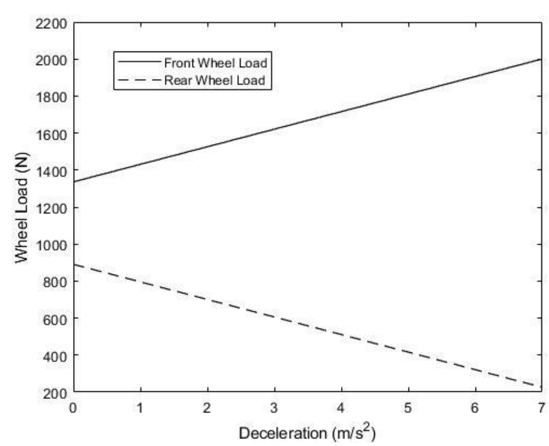

Figure 6. Instantaneous wheel loads as a function of deceleration.

5.3.3 Influence of Dynamic Weight Transfer

As the motorcycle experiences dynamic weight transfer, the ability of each tire to generate braking force is altered. Under static conditions, the maximum braking force that a tire is capable of generating is defined by the following relationship:

$$F_{bf}^{max} = \mu_p W_f \quad (40)$$

$$\therefore F_{bf}^{max} = 0.8 \times 1336.122\ \mathrm{N} = 1068.898\ \mathrm{N}$$

And,

$$F_{br}^{max} = \mu_p W_r \quad (41)$$

$$\therefore F_{br}^{max} = 0.8 \times 890.748\ \mathrm{N} = 712.598\ \mathrm{N}$$

However, as a result of dynamic weight transfer during deceleration, the maximum braking force that a tire can generate is modified as follows:

$$F_{bf}^{max} = \mu_p W_f' \quad \text{(From equation 15)}$$

$$\therefore F_{bf}^{max} = 0.8 \times 2080.998\ \mathrm{N} = 1664.798\mathrm{N}$$

And,

$$F_{br}^{max} = \mu_p W_r' \quad \text{(From equation 16)}$$

$$\therefore F_{br}^{max} = 0.8 \times 145.872\ \mathrm{N} = 116.698\ \mathrm{N}$$

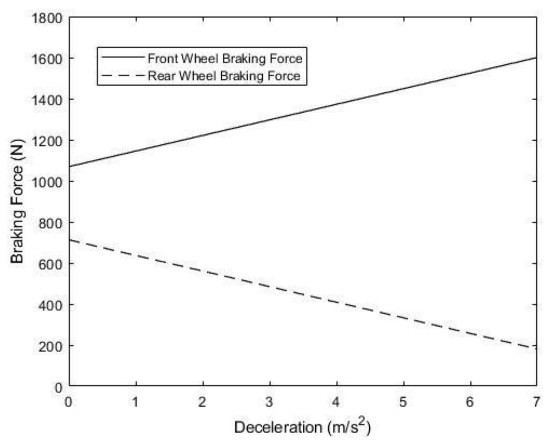

Figure 7. Front and rear wheel braking force as a function of deceleration.

Weight transfer, therefore, increases the ability of the front tire to generate braking force whilst decreasing that of the rear tire.

5.3.4 Braking at the Front Wheel

Assuming that the brake is applied only at the front wheel, maximum braking force that the front tire can generate will be equal to the peak coefficient friction available at the tire-road interface multiplied by the load on the wheel. The equation for maximum deceleration under front wheel braking is as follows;

$$d_f^{max} = g\frac{\mu_p\left[\frac{d}{L}\right]}{1-\mu_p\left[\frac{h}{L}\right]} \quad \text{(From equation 24)}$$

$$\therefore d_f^{max} = 9.81\ \mathrm{m/s^2} \times \frac{0.8\left[\frac{861\ \mathrm{mm}}{1435\ \mathrm{mm}}\right]}{1-0.8\left[\frac{600\ \mathrm{mm}}{1435\ \mathrm{mm}}\right]} = 7.076\ \mathrm{m/s^2}$$

The maximum braking force in this case can be calculated using the following equation;

$$F_{bf}^{max} = \frac{\mu_p\left[W_f + \frac{h}{L}F_{br}\right]}{1-\mu_p\frac{h}{L}} \quad \text{(From equation 19)}$$

Putting $F_{br} = 0$ in the equation above;

$$F_{bf}^{max} = \frac{0.8 \times \left[1336.122\ \mathrm{N} + \frac{600\ \mathrm{mm}}{1435\ \mathrm{mm}} \times 0\mathrm{kg.f}\right]}{1-0.8 \times \frac{600\ \mathrm{mm}}{1435\ \mathrm{mm}}} = 1606.145\ \mathrm{N}$$

5.3.5 Braking at the Rear Wheel

A similar treatment can be made if the brake is applied only at the rear wheel. In this case, the maximum braking force that the rear tire can generate will be equal to the peak coefficient friction available at the road-tire interface multiplied by the load on the wheel. The equation for maximum deceleration under rear wheel braking is as follows;

$$d_r^{max} = g\frac{\mu_p\left[\frac{c}{L}\right]}{1+\mu_p\left[\frac{h}{L}\right]} \quad \text{(From equation 25)}$$

$$\therefore d_r^{max} = 9.812\ \mathrm{m/s^2} \times \frac{0.8\left[\frac{574\ \mathrm{mm}}{1435\ \mathrm{mm}}\right]}{1+0.8\left[\frac{600\ \mathrm{mm}}{1435\ \mathrm{mm}}\right]}$$

$$\therefore d_r = 2.352\ \mathrm{m/s^2}$$

The maximum braking force in this case can be calculated using the following equation:

$$F_{br}^{max} = \frac{\mu_p\left[W_r - \frac{h}{L}F_{bf}\right]}{1+\mu_p\frac{h}{L}} \quad \text{(From equation 20)}$$

Putting $F_{bf} = 0$ in the equation above, we get:

$$F_{br}^{max} = \frac{0.8 \times \left[890.748\ \mathrm{N} - \frac{600\ \mathrm{mm}}{1435\ \mathrm{mm}} \times 0\mathrm{N}\right]}{1+0.8 \times \frac{600\ \mathrm{mm}}{1435\ \mathrm{mm}}} = 533.984\ \mathrm{N}$$

5.3.6 Braking at Both Wheels

Assuming that the total braking force (F_b^{total}) of the motorcycle is distributed between the front and the rear wheels in a ratio (K_f) such that the brake force applied on the front wheel is;

$$F_{bf} = K_f F_b^{total} \quad \text{(From equation 26)}$$

And the remainder of the brake force goes to the rear wheel;

$$F_{br} = (1 - K_f)F_b^{total} \qquad \text{(From equation 27)}$$

This dictates that $K_f = 1$ when all the braking force is directed to the front wheel and $K_f = 0$ when all the braking force is directed to the rear wheel.

The total retarding force developed by the combined braking action at both the wheels is;

$$F_b^{total} = F_{bf} + F_{br} \qquad \text{(Using equation 7)}$$

Maximum braking force on the front wheel is dependent on that present on the rear axle through the deceleration and associated forward weight transfer resulting from the rear brake action. The maximum braking force at the front and the rear wheel are given by the following equations;

$$F_{bf}^{max} = \frac{\mu_p\left[W_f + \frac{h}{L}F_{br}\right]}{1 - \mu_p\frac{h}{L}} \qquad \text{(From equation 19)}$$

$$F_{br}^{max} = \frac{\mu_p\left[W_r - \frac{h}{L}F_{bf}\right]}{1 + \mu_p\frac{h}{L}} \qquad \text{(From equation 20)}$$

These relationships can be best visualized by plotting the rear versus the front brake forces as show in Figure 10.

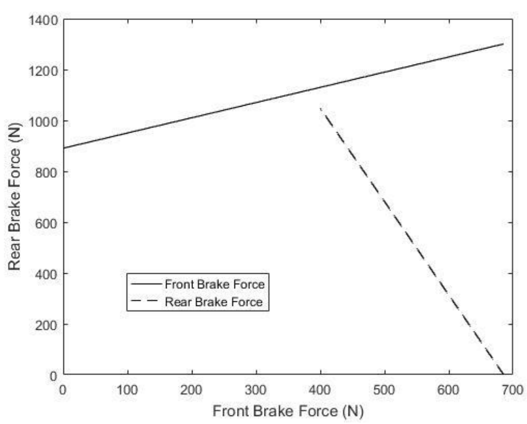

Figure 8. Maximum braking forces at the front and rear wheels.

Assuming the front brake force distribution factor (K_f) of the braking system to be 0.5, the deceleration associated with the front wheel lock-up condition can be calculated as follows;

$$d_f = g\frac{\mu_p\left(1 + \frac{1-K_f}{K_f}\right)\left(\frac{d}{L}\right)}{\left[1 - \mu_p\left(1 + \frac{1-K_f}{K_f}\right)\left(\frac{h}{L}\right)\right]} \qquad \text{(From equation 33)}$$

$$\therefore d_f = 9.81\ \mathrm{m/s^2} \times \frac{0.8 \times \left(1 + \frac{1-0.5}{0.5}\right)\left(\frac{861\ \mathrm{mm}}{1435\ \mathrm{mm}}\right)}{\left[1 - 0.8 \times \left(1 + \frac{1-0.5}{0.5}\right)\left(\frac{600\ \mathrm{mm}}{1435\ \mathrm{mm}}\right)\right]}$$

$$\Rightarrow d_f = 28.451\ \mathrm{m/s^2}$$

Similarly, the deceleration associated with the rear wheel lock-up condition is;

$$d_r = g\frac{\mu_p\left(1 + \frac{K_f}{1-K_f}\right)\left(\frac{c}{L}\right)}{\left[1 + \mu_p\left(1 + \frac{K_f}{1-K_f}\right)\left(\frac{h}{L}\right)\right]} \qquad \text{(From equation 36)}$$

$$\therefore d_r = 9.81\ \mathrm{m/s^2} \times \frac{0.8 \times \left(1 + \frac{0.5}{1-0.5}\right)\left(\frac{574\ \mathrm{mm}}{1435\ \mathrm{mm}}\right)}{\left[1 + 0.8 \times \left(1 + \frac{0.5}{1-0.5}\right)\left(\frac{600\ \mathrm{mm}}{1435\ \mathrm{mm}}\right)\right]}$$

$$\Rightarrow d_r = 3.762\ \mathrm{m/s^2}$$

For $0 \le K_f \le 1$, the deceleration values associated with the assumptions of front and rear wheel lock-ups are given in Table 1.

Table 1. Deceleration under front and rear lock-up assumptions for numerous front brake force distribution factors.

K_f	$\lvert d_f \rvert$ (m/s^2)	$\lvert d_r \rvert$ (m/s^2)
0.0001	14.082	**2.353**
0.05	16.551	**2.444**
0.1	20.081	**2.543**
0.15	25.523	**2.650**
0.2	35.011	**2.767**
0.25	55.729	**2.895**
0.3	136.508	**3.035**
0.35	303.691	**3.189**
0.4	71.884	**3.359**
0.45	40.767	**3.549**
0.5	28.451	**3.762**
0.55	21.850	**4.002**
0.6	17.735	**4.274**
0.65	14.925	**4.586**
0.7	12.883	**4.948**
0.75	11.333	**5.371**
0.8	10.115	**5.873**
0.85	9.134	**6.479**
0.9	8.327	**7.225**
0.9345	**7.848**	7.848
0.95	**7.650**	8.164
0.9999	**7.077**	9.382

If $|d_f|<|d_r|$, it indicates that the front wheel locks-up ahead of the rear wheel. If $|d_f|>|d_r|$, then the rear wheel locks-up first.

The observation made is that by modulating only the brake force distribution factor, simultaneous lock-ups at both wheels of the motorcycle is attainable, the case in which both the tires are doing the maximum work in decelerating the motorcycle. This is achieved at a point where$|d_f| = |d_f|$.

In the case of a front wheel lock up, the limiting value of deceleration is that generated by the front tire, and therefore the dynamic wheel loads are expressed with the following equations;

$$W_f' = \frac{m\times g\times d}{L} + \frac{m\times|d_f|\times h}{L} \quad (42)$$

$$W_r' = \frac{m\times g\times c}{L} - \frac{m\times|d_f|\times h}{L} \quad (43)$$

Similarly, in the case of rear wheel lock-up occurring prior to front wheel lock-up, the following equations will dictate the dynamic wheel loads.

$$W_f' = \frac{m\times g\times d}{L} + \frac{m\times|d_r|\times h}{L} \quad (44)$$

$$W_r' = \frac{m\times g\times c}{L} - \frac{m\times|d_r|\times h}{L} \quad (45)$$

For $K_f = 0.5$

$$|d_f| = 28.451\ m/s^2$$

$$|d_r| = 3.762\ m/s^2$$

Thus indicating a rear wheel lock-up prior to the front wheel lock-up.
Using equation (44) and (45);

$$W_f' = \frac{m\times g\times d}{L} + \frac{m\times|d_r|\times h}{L} = \frac{227\ kg\ \times 9.81\ m/s^2\times 861mm}{1435\ mm} + \frac{227\ kg\times 3.762\ m/s^2\times 600mm}{1435\ mm}$$

$$\therefore W_f' = 1693.184\ N$$

$$W_r' = \frac{m\times g\times c}{L} - \frac{m\times|d_r|\times h}{L} = \frac{227\ kg\ \times 9.81\ m/s^2\times 574mm}{1435\ mm} - \frac{227\ kg\times 3.762\ m/s^2\times 600mm}{1435\ mm}$$

$$\therefore W_f' = 533.686\ N$$

For $0 \le K_f \le 1$, the dynamic wheel loads associated with the assumptions of front and rear wheel lock-ups are given in Table 2.

Table 2. Dynamic wheel loads under front and rear lock-up assumptions for numerous front brake force distribution factors.

K_f	W_f' (N)	W_r' (N)
0.0001	1559.407	667.463
0.05	1568.081	658.789
0.1	1577.476	649.394
0.15	1587.664	639.206
0.2	1598.750	628.120
0.25	1610.859	616.011
0.3	1624.138	602.732
0.35	1638.765	588.105
0.4	1654.958	571.912
0.45	1672.982	553.888
0.5	1693.165	533.705
0.55	1715.921	510.949
0.6	1741.776	485.094
0.65	1771.407	455.463
0.7	1805.709	421.161
0.75	1845.879	380.991
0.8	1893.565	333.305
0.85	1951.094	275.776
0.9	2021.862	205.008
0.9345	**2080.998**	**145.872**
0.95	2062.234	164.636
0.9999	2007.782	219.088

In the event of front wheel lock-up occurring ahead of rear wheel lock-up, the braking forces that the front and rear tires can generate are given by the following expressions;

$$F_{bf} = \mu_p W_f' \quad \text{(From equation 15)}$$

$$F_{br} = \frac{1-K_f}{K_f}\times F_{bf} \quad \text{(From equation 29)}$$

In the event of a rear wheel lock-up occurring ahead of front wheel lock-up, the braking forces produces at the front and rear tires are given by the following expressions;

$$F_{br} = \mu_p W_r' \quad \text{(From equation 16)}$$

$$F_{bf} = \frac{K_f}{1-K_f}\times F_{br} \quad \text{(From equation 28)}$$

For $K_f = 0.5$, rear wheel locks up first and the dynamic wheel loads are;

$$W_f' = 1693.165\ N$$

$$W_r' = 533.705\ N$$

Therefore the braking forces at the front and rear wheels are given by equations (16) and (28).

$$\therefore F_{br} = \mu_p W_r' = 0.8 \times 533.705 \text{ N} = 426.964 \text{ N}$$

$$\therefore F_{bf} = \frac{K_f}{1-K_f} \times F_{br} = \frac{0.5}{1-0.5} \times 426.964 \text{ N} = 426.964 \text{ N}$$

While the total braking force generated by the motorcycle is given by;

$$F_b^{total} = F_{bf} + F_{br} \qquad \text{(Using equation 7)}$$

$$\therefore F_b^{total} = 426.964 \text{ N} + 426.964 \text{ N} = 853.928 \text{ N}$$

For $0 \le K_f \le 1$, the braking forces generated by the front and rear tires associated with the assumptions of front and rear lockups are given in Table 3.

Table 3. Front and rear braking forces under front and rear lock-up assumptions for numerous front brake force distribution factors.

K_f	F_{bf} (N)	F_{br} (N)	F_b^{total} (N)
0.0001	0.053402	533.970	534.024
0.05	27.73847	527.031	554.769
0.1	57.72389	519.515	577.239
0.15	90.2408	511.365	601.605
0.2	125.624	502.496	628.120
0.25	164.270	492.809	657.079
0.3	206.651	482.186	688.837
0.35	253.337	470.484	723.821
0.4	305.020	457.530	762.549
0.45	362.545	443.111	805.656
0.5	426.964	426.964	853.928
0.55	499.594	408.759	908.353
0.6	582.113	388.075	970.189
0.65	676.687	364.370	1041.057
0.7	786.167	336.929	1123.096
0.75	914.377	304.792	1219.170
0.8	1066.575	266.644	1333.219
0.85	1250.186	220.621	1470.807
0.9	1476.056	164.006	1640.062
0.9345	**1664.799**	**116.697**	**1781.496**
0.95	1649.787	86.831	1736.618
0.9999	1606.225	0.161	1606.386

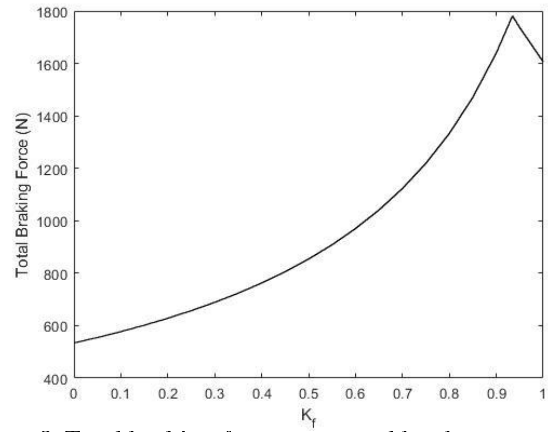

Figure 9. Total braking force generated by the motorcycle at incipient lockup condition as a function of front brake force distribution factor.

Deceleration (d_x) of the motorcycle is calculated by dividing the total braking force generated by the motorcycle by its mass (m).

$$d_x = \frac{F_b^{total}}{m} \tag{46}$$

For $K_f = 0.5$, the total braking force is;

$$F_b^{total} = 1781.496 \text{ N}$$

$$\therefore d_x = \frac{853.928 \text{ N}}{227 \text{ kg}} = 3.762 \text{ m/s}^2$$

For $0 \le K_f \le 1$, the deceleration achieved by the motorcycle associated with the assumptions of front and rear wheel lock-ups are given in Table 4.

Table 4. Deceleration achieved by the motorcycle under front and rear lock-up assumptions for numerous front brake force distribution factors.

K_f	F_b^{total} (N)	d_x (m/s²)
0.0001	534.024	2.353
0.05	554.769	2.444
0.1	577.239	2.543
0.15	601.605	2.650
0.2	628.120	2.767
0.25	657.079	2.895
0.3	688.837	3.035
0.35	723.821	3.189
0.4	762.549	3.359
0.45	805.656	3.549
0.5	853.928	3.762
0.55	908.353	4.002
0.6	970.189	4.274

0.65	1041.057	4.586
0.7	1123.096	4.948
0.75	1219.170	5.371
0.8	1333.219	5.873
0.85	1470.807	6.479
0.9	1640.062	7.225
0.9345	**1781.496**	**7.848**
0.95	1736.618	7.650
0.9999	1606.386	7.077

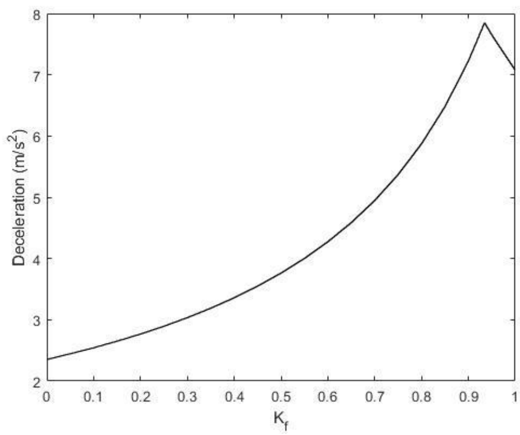

Figure 10. Deceleration achieved by the motorcycle at incipient lockup condition as a function of front brake force distribution factor.

Braking efficiency (η_b) is defined as the ratio of the maximum deceleration rate in g-units achievable prior to any tire lock-up to the coefficient of friction of road adhesion (μ_p) and is given by;

$$\eta_b = \frac{d_x/g}{\mu_p} \tag{47}$$

The braking efficiency indicates the extent to which the vehicle utilizes the available coefficient of road adhesion for braking. Thus, when $d_x/g < \mu$, hence for $\eta_b < 1.0$, the deceleration is less than the maximum achievable, resulting in an unnecessary long stopping distance. [9]

At $K_f = 0.5$, the deceleration of the motorcycle is 3.762 m/s². Consequently, the braking efficiency is;

$$\eta_b = \frac{d_x/g}{\mu}$$

$$= \frac{3.762\ m/s^2 / 9.81\ m/s^2}{0.8} = 0.479$$

For $0 \leq K_f \leq 1$, the overall braking efficiencies of the braking system associated with the assumptions of front and rear lockups are given in Table 5.

Table 5. Braking efficiency achieved by the motorcycle under front and rear lock-up assumptions for numerous front brake force distribution factors.

K_f	d_x (m/s²)	η_b
0.0001	2.353	0.300
0.05	2.444	0.311
0.1	2.543	0.324
0.15	2.650	0.338
0.2	2.767	0.353
0.25	2.895	0.369
0.3	3.035	0.387
0.35	3.189	0.406
0.4	3.359	0.428
0.45	3.549	0.452
0.5	3.762	0.479
0.55	4.002	0.510
0.6	4.274	0.545
0.65	4.586	0.584
0.7	4.948	0.630
0.75	5.371	0.684
0.8	5.873	0.748
0.85	6.479	0.826
0.9	7.225	0.921
0.9345	**7.848**	**1.000**
0.95	7.650	0.975
0.9999	7.077	0.902

Integrating the deceleration of a body in motion with respect to time allows for the determination of speed. Integrating yet again allows for the determination of position. Applying this relationship to a motorcycle experiencing linear deceleration, the theoretical stopping distance (SD) of a motorcycle in motion can be calculated as follows [10];

$$SD = \frac{v^2}{2d_x} \tag{48}$$

Assuming the motorcycle braking from an initial speed of 30 m/s to a complete stop under constant deceleration at the condition of $K_f = 0.5$;

$$SD = \frac{v^2}{2d} = \frac{(30\ m/s^2)^2}{2 \times 3.762\ m/s^2} = 119.617\ m$$

For $0 \leq K_f \leq 1$, the stopping distances of the motorcycle from an initial speed of 30 m/s associated with the assumptions of front and rear wheel lock-ups are given in Table 6.

Table 6. Stopping distance of the motorcycle from an initial speed of 30 m/s under front and rear lock-up assumptions for numerous front brake force distribution factors.

K_f	d_x (m/s^2)	SD (m)
0.0001	2.353	191.284
0.05	2.444	184.131
0.1	2.543	176.963
0.15	2.650	169.796
0.2	2.767	162.628
0.25	2.895	155.461
0.3	3.035	148.293
0.35	3.189	141.126
0.4	3.359	133.959
0.45	3.549	126.791
0.5	3.762	119.624
0.55	4.002	112.456
0.6	4.274	105.289
0.65	4.586	98.121
0.7	4.948	90.954
0.75	5.371	83.787
0.8	5.873	76.619
0.85	6.479	69.452
0.9	7.225	62.284
0.9345	**7.848**	**57.339**
0.95	7.650	58.821
0.9999	7.077	63.590

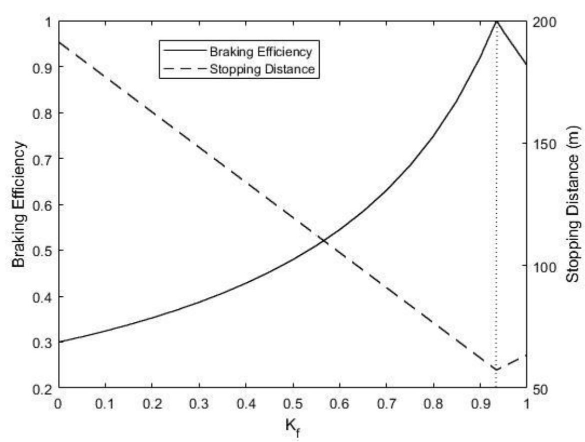

Figure 11. Braking efficiency achieved by the motorcycle at incipient lockup condition and corresponding stopping distance as a function of front brake force distribution factor.

For $K_f = 0.5$, rear wheel locks up first and the dynamic wheel loads are;

$$W_f' = 1693.165 \text{ N}$$
$$W_r' = 533.705 \text{ N}$$

Therefore the front weight bias of the motorcycle is;

$$\frac{W_f'}{W} = \frac{1693.165 \text{ N}}{2226.87 \text{ N}} = 0.7603$$

For $0 \leq K_f \leq 1$, the front weight biases of the motorcycle, experiencing constant deceleration, associated with the assumptions of front and rear wheel lock-ups are given in Table 7.

Table 7. Front weight bias of the motorcycle under front and rear lock-up assumptions for numerous front brake force distribution factors.

K_f	W_f' (N)	W_r' (N)	SD (m)	$\frac{W_f'}{W}$
0.0001	1559.407	667.463	191.284	0.7003
0.05	1568.081	658.789	184.131	0.7042
0.1	1577.476	649.394	176.963	0.7084
0.15	1587.664	639.206	169.796	0.7130
0.2	1598.750	628.120	162.628	0.7179
0.25	1610.859	616.011	155.461	0.7234
0.3	1624.138	602.732	148.293	0.7293
0.35	1638.765	588.105	141.126	0.7359
0.4	1654.958	571.912	133.959	0.7432
0.45	1672.982	553.888	126.791	0.7513
0.5	1693.165	533.705	119.624	0.7603
0.55	1715.921	510.949	112.456	0.7706
0.6	1741.776	485.094	105.289	0.7822
0.65	1771.407	455.463	98.121	0.7955
0.7	1805.709	421.161	90.954	0.8109
0.75	1845.879	380.991	83.787	0.8289
0.8	1893.565	333.305	76.619	0.8503
0.85	1951.094	275.776	69.452	0.8762
0.9	2021.862	205.008	62.284	0.9079
0.9345	**2080.998**	**145.872**	**57.339**	**0.9345**
0.95	2062.234	164.636	58.821	0.9261

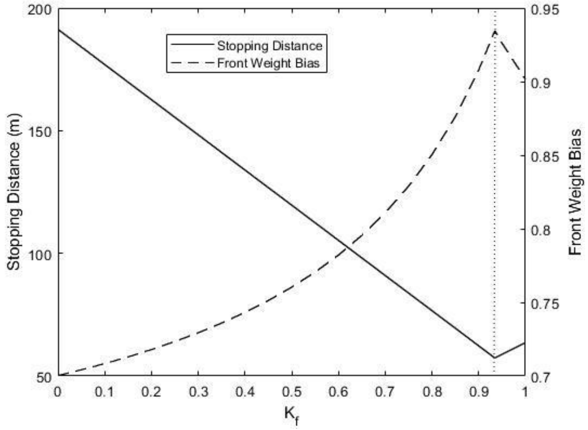

Figure 12. Stopping distance of the motorcycle and its front weight bias at incipient lockup condition as a function of front brake force distribution factor.

The observation made is that modulation of front brake force distribution factor (K_f) in a motorcycle results in variation of the overall braking efficiency (η_b) attained by the braking system, thus altering the stopping distance of the motorcycle. The point at which the system achieves the maximum braking efficiency and minimum stopping distance is when the front brake force distribution factor is equal in magnitude to instantaneous front weight bias of the motorcycle.

$$\frac{F_{bf}}{F_b^{total}} = \frac{W_f'}{W} \tag{49}$$

Statistical analysis of deceleration of the motorcycle in slippery road conditions with $\mu_p = 0.3$, as compiled in Table 8, vindicates that equation (49) holds true irrespective of peak coefficient of friction available at the tire-road interface.

Table 8. Front weight bias of the motorcycle under front and rear lock-up assumptions for numerous front brake force distribution factors in slippery road conditions.

K_f	W_f' (N)	W_r' (N)	SD (m)	$\frac{W_f'}{W}$
0.0001	1435.409	791.461	430.174	0.6446
0.05	1440.016	786.854	411.099	0.6467
0.1	1445.082	781.788	391.986	0.6489
0.15	1450.667	776.203	372.873	0.6514
0.2	1456.856	770.014	353.760	0.6542
0.25	1463.752	763.118	334.647	0.6573
0.3	1471.483	755.387	315.533	0.6608
0.35	1480.211	746.659	296.420	0.6647
0.4	1490.142	736.728	277.307	0.6692
0.45	1501.543	725.327	258.194	0.6743
0.5	1514.768	712.102	239.081	0.6802
0.55	1530.291	696.579	219.968	0.6872
0.6	1548.767	678.103	200.855	0.6955
0.65	1571.131	655.739	181.741	0.7055
0.7	1598.750	628.120	162.628	0.7179
0.7254	**1615.451**	**611.419**	**152.905**	**0.7254**
0.75	1604.464	622.406	159.165	0.7205
0.8	1584.574	642.296	171.907	0.7116
0.85	1567.429	659.441	184.649	0.7039
0.9	1552.498	674.372	197.392	0.6972
0.95	1539.377	687.493	210.134	0.6913
0.9999	1527.779	699.091	222.850	0.6861

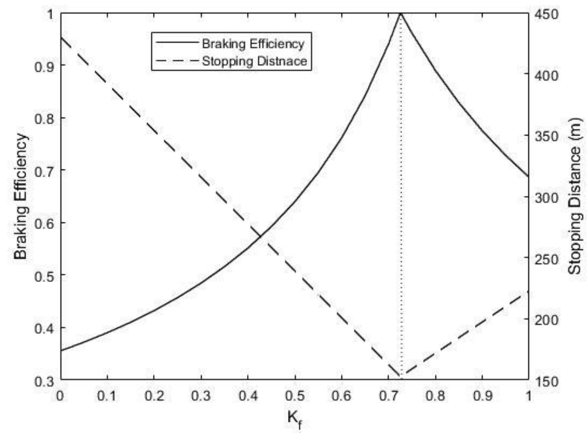

Figure 13. Stopping distance of the motorcycle and its front weight bias at incipient lockup condition as a function of front brake force distribution factor in slippery road conditions.

A method of attaining simultaneous front and rear wheel lock-up is by ensuring that the front brake force distribution factor is equal in magnitude to the instantaneous front weight bias of the motorcycle in braking. (As expressed in equation 49). Since the optimum front brake force distribution factor is a function of motorcycle's geometry and the peak friction coefficient of friction available on a surface, a mathematic equation can be derived by scripting the braking forces of the system as a function of motorcycle's geometry.

$$K_f^o = \frac{F_{bf}}{F_b^{total}} \tag{50}$$

Where K_f^o is the optimum front brake force distribution factor.

$$\Rightarrow K_f^o = \frac{W_f'}{W} \qquad \text{(Using equation 49)}$$

$$\Rightarrow K_f^o = \frac{\frac{mgd}{L} + \frac{md_xh}{L}}{mg} \qquad \text{(Using equation 10)}$$

$$\Rightarrow K_f^o = \frac{d}{L} + \frac{d_xh}{gL} \tag{51}$$

Since the upper limit of deceleration for a motorcycle is determined by the peak coefficient of friction available at the tire-road interface;

$$\Rightarrow K_f^o = \frac{d}{L} + \frac{\mu_p g h}{g L} \qquad \text{(Using equation 39)}$$

$$\therefore K_f^o = \frac{d + \mu_p h}{L} \qquad (52)$$

6 Conclusion

Modulation of the front brake force distribution factor of a motorcycle enables attainment of peak braking efficiency of the system whilst ensuring minimum stopping distance. Braking efficiency of the system is maximized when the front brake force distribution factor of the motorcycle equals its instantaneous front weight bias in the event of deceleration. Therefore, load sensing brake force distribution between the front and rear wheels of a motorcycle such that the brake force distribution factor equals its instantaneous front weight bias is a favourable mechanism of enhancing the braking performance of the motorcycle. Such a load sensing brake force distribution system would eliminate the dependency of the braking system on rigid constraints and rider judgement, thus facilitating the system to account for loading conditions and dynamic weight transfer at any dynamic braking condition and to adjust the relative hydraulic pressure applied to the front and rear brake calipers in order to maximize overall braking efficiency of the motorcycle and minimize its stopping distance.

References

[1]. Jeffery K. Ball, Richard Stone, "Automotive Engineering Fundamentals", Society of Automotive Engineers, 2004. ISBN 9780768009873.
[2]. Rao V. Dukkipati, Jian Pang, Mohamad S. Qatu, Gang Sheng, Zuo Shuguang, "Road Vehicle Dynamics", Society of Automotive Engineers, 2008. ISBN 9780768016437
[3]. Thomas D. Gillespie, "Fundamentals of Vehicle Dynamics", Society of Automotive Engineers, 1992. ISBN 9781560911999
[4]. *Lieh, Junghsen,* "Closed-form Method to Evaluate Bike Braking Performance", Human Power eJournal, Article 19, Issue 7, April 24, 2013.
[5]. John Forester, "Effective Cycling", MIT Press, 2012. ISBN 9780262516945
[6]. https://www.sheldonbrown.com/brakturn.html
[7]. William F. Milliken, Douglas L. Milliken, "Race Car Vehicle Dynamics, Society of Automotive Engineers, 1994. ISBN 9781560915263
[8]. https://motogp.hondaracingcorporation.com/rc213v-2018/
[9]. Jo Y. Wong, "Theory of Ground Vehicles", John Wiley & Sons, 2008. ISBN 9780470170380.
[10]. James Walker, "The Physics of Braking Systems", StopTech LLC, 2005.