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High-Speed Motorcycle Dynamics: Quick Turns While Going Straight and Around Curves

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ABSTRACT
In this paper we present analyses and then explanations for two anti-intuitive motorcycle maneuvers: 1) sudden steering while going straight ahead at high speed; and 2) firm, but brief, rear wheel braking while going at high speed around a curve. Using the principles of dynamics (Newton's laws), the law of gyroscopes, and stick/slip tire behavior, we show that pushing on the handle bar as to turn right (or left) causes the motorcycle instead to go left (or right); and that sudden rear wheel braking when nearly sliding out in a curve, redirects the motorcycle toward the center of the curve, and at a slower speed.
Keywords – control, human factors, motorcycles, stability, vehicle dynamics

I. Introduction

Motorcyclists know that when going around a curve, it is necessary to "lean into the turn" [1]. That is, the operator leans to the left (or right) to make a turn to the left (or right).
Expressed another way: "The way you lean is the way you go."

Experienced motorcyclists also know that at higher speeds, a quick turn can be made by a sudden, but brief, push, or pull, on one of the handle grips. Intuitively one might expect the motorcycle to turn in the direction of the push, or pull. But just the <u>opposite</u> occurs! If the operator pushes quickly, but firmly, on the right handle grip, instead of going left, the motorcycle turns to the right! (and conversely).

What is less well known is that if in a curve, at relatively high speed, an operator senses that he (or she) is losing control, drifting too far toward the outside of the curve, and in danger of possibly "sliding out", he (or she) can quickly regain control by a brief, but firm, application of the rear brake. Surprisingly, this brief rear wheel braking causes the motorcycle to turn back toward the center of the curve, at a slightly reduced speed, and in a more upright and stable configuration.

In this paper we discuss the dynamics behind both of these extraordinary maneuvers, explaining why they occur.

II. Law of Gyroscopes

To begin, it is helpful to review the "law of gyroscopes" – a long established principle of classical physics. Its application with motorcycles is via the modeling of motorcycle wheels as gyrostats – that is, by recognizing that a motorcycle is dynamically similar to the rotating disk (the gyrostat) of a gyroscope, thus experiencing the same kinds of forces and moments.

Fig. 1 presents a line drawing sketch of a gyroscope. It consists of a rotating disk and supporting frames (gimbals) which allow the disk gyrostat to have an arbitrary orientation.

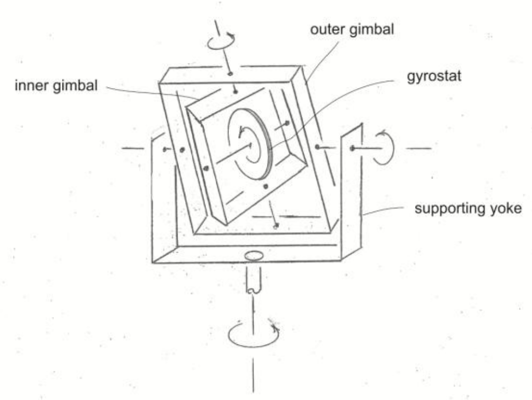

Fig. 1 Gyroscope

The law of gyroscopes asserts that if a gyrostat is made to turn about an axis different from its axis of rotation, the gyrostat will attempt to align its rotation axis with the imposed axis of rotation, and with the same rotation direction [2].

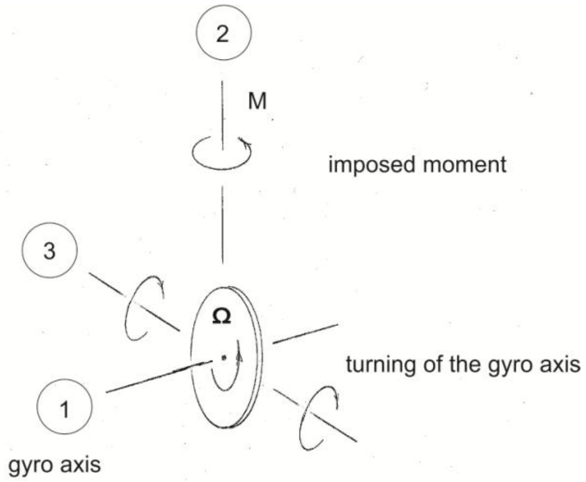

Fig. 2. Gyrostat response to an imposed movement

Fig. 2 illustrates the principle. In the figure, the gyro axis (axis 1) is turning toward the imposed rotation axis (axis 2), about the third axis (axis 3).

The validity of the law of gyroscopes may be established experimentally using a laboratory gyroscope and/or analytically using Newton's laws and Euler's dynamical equations [3].

III. QUICK, FIRM HANDLEBAR TURN

We can use the law of gyroscopes to explain the response of a rapidly travelling motorcycle to a sudden handlebar turn. To this end, consider an overhead view of a motorcycle traveling from West to East as in Fig. 3.

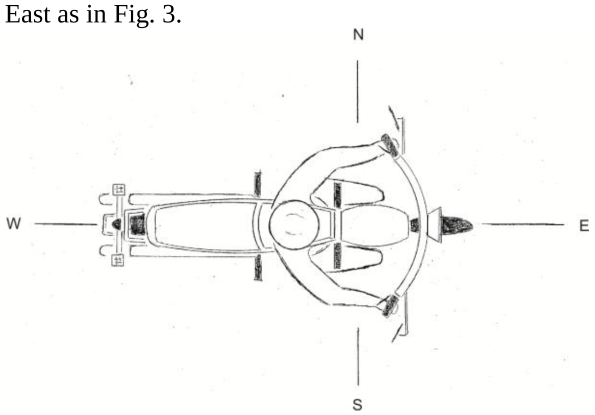

Fig. 3 Overhead view of a motorcycle

In this configuration, the axes of rotation of the wheels is directed North (using the "right-hand" rule).

Next suppose that the operator momentarily pulls on the right handle grip (toward the rear), or alternatively, pushes forward on the left handle grip, as represented in Fig. 4. Then the imposed rotation axis on the front wheel is directed down. By thinking of the front wheel as a gyrostat, and then applying the law of gyroscopes, we see that the wheel will respond by turning its rotation axis toward the imposed axis of rotation. Since the wheel's rotation axis is directed left (or North), and the imposed rotation axis is directed down, the wheel will turn its rotation axis down and cause the motorcycle and operator to lean to the left (or North).

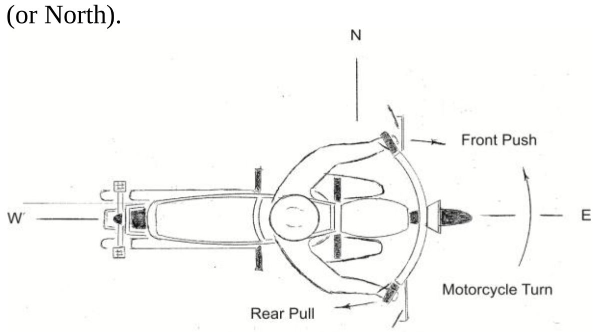

Fig. 4. Momentary sudden right steer and left turn

Finally, by remembering the maxim: "you go the way you lean," the motorcycle will turn to the left (or North), just opposite of the sudden, but short, steering direction!

Similarly, a quick sudden push forward on the right handle grip causes the motorcycle to turn to the right (or South).

IV. STICK/SLIP, NORMAL/FRICTION FORCES

While the law of gyroscopes helps in understanding the overall behavior of motorcycle wheels, we need a friction and deformation analysis to understand tire/road contact dynamics. Contact problems are among the most difficult problems in all of engineering mechanics. Nevertheless, K. L. Johnson [4] provides an excellent treatise describing current understanding in contact mechanics.

Consider the elementary problem of a rigid homogeneous block B on a flat horizontal surface S, being pulled along the surface with a force F as represented in Fig. 5. Let μ be the coefficient of friction between B and S. The uniformly distributed vertical (normal) forces exerted by S on the lower surface of B are equivalent to a single force N. Let W be the weight of B. Then with S being horizontal, N is equal to W.

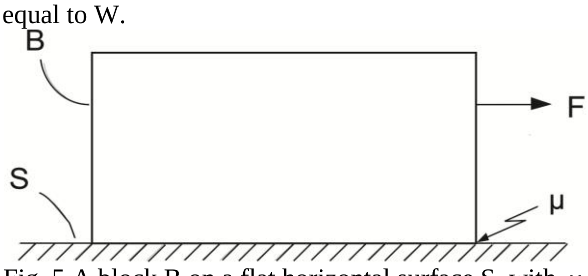

Fig. 5 A block B on a flat horizontal surface S, with μ being the friction coefficient between B and S

As long as F is less than μN , B will not slide but instead remain of rest on S. If, however, F is steadily increased so that it reaches the value: μN , B will begin to slide.

Interestingly, after sliding begins the magnitude of F needed to maintain sliding is *less than* μN . This finding has prompted textbook writers to introduce two coefficients of friction: μ_s and μ_d representing the "static" and "dynamic" (or moving) cases. Then we have the inequality:

$$\mu_d < \mu_s \quad (1)$$

where μ_d can be as much as 25% smaller than μ_s [5].

Next, consider what happens when B is no longer rigid but instead deformable: when the pull force F is applied to B, B will elongate at the end of B, where F is applied. The force distribution between B and S is then no longer uniform, but instead lower at the end where F is applied. It is lower at this end because as B is elongating, it is sliding (or "slipping") on S. That is, in view of (1), the friction force per unit area at the slipping end of B is less than that of the static (or "stick") end of B.

Fig. 6 illustrates the stick/slip phenomena.

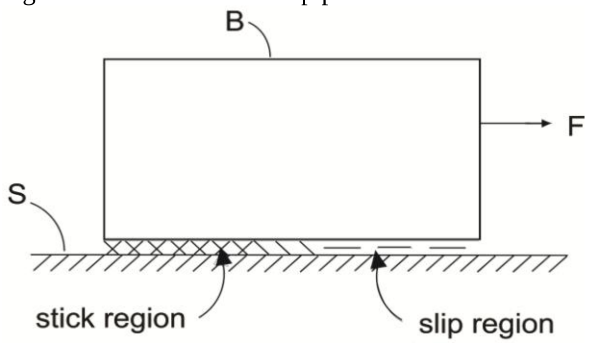

Fig. 6 Stick and slip regions of a deformable block being stretched

V. Tire/Roadway Interaction

To apply the stick/slip concepts with motorcycle tires on a roadway, consider first the ideal geometry case of a rigid circular wheel (or disk) D rolling on a flat horizontal rigid surface S as in Fig. 7. With ideal geometry there is one, and only one, point of contact C between D and S. Also with this geometry D will roll indefinitely on S, at a constant speed, and without slipping. The contact surface of D (the rim) and the surface of S are then said to be "perfectly rough".

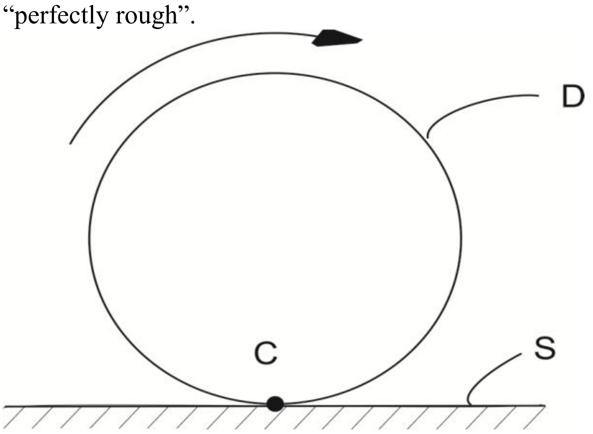

Fig. 7. A rigid wheel rolling on a flat, horizontal rigid surface

Although "perfectly rough" surfaces do not physically exist, the model of Fig. 7 is nevertheless useful for many physical analyses. In this latter regard, with no slipping between D and S, the contact point C, belonging to D, has *zero velocity* at the instant of its (1) contact with S. That is,

$$V_C = 0 \quad (2)$$

Also, with D rolling on S at a constant speed, the force exerted by S on D is vertical. That is, there is no horizontal "tractive" force.

Next, suppose the contacting surfaces of D and S are not "perfectly rough", but are "perfectly smooth". Then D can simply slide on S without having any rotation (or angular speed).

Consider now a tire T on a flat horizontal roadway surface R, as in Fig. 8. Neither T nor R are rigid, nor are they "perfectly rough" or "perfectly smooth". The roadway surface R, however, is considerably stiffer than the tire T. Therefore, for practical purposes in our analysis we can consider R to be virtually rigid.

Since T is deformable, there is not just one contact point between T and R but instead an entire "contact patch" of points as represented in Fig. 8. The notions

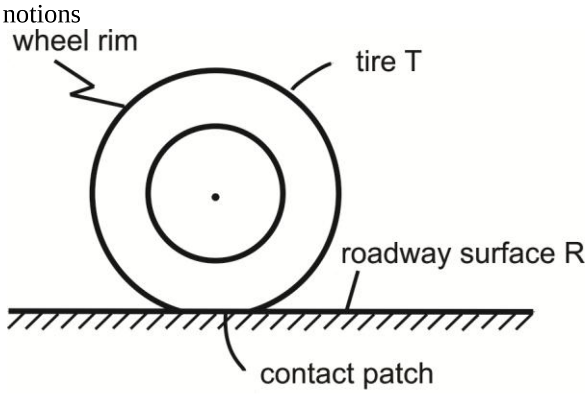

Fig. 8. A tire T on a roadway surface R

of "rolling" and "slipping" now become more varied and detailed. There are, in essence, four cases to consider:

1. "*Rolling*": This occurs if all points of T in the contact patch have *zero* velocity relative to the roadway R.
2. "*Sliding*" or "*Skidding*": This occurs if all points of T in the contact patch have *non-zero* velocity relative to R *and* the wheel rim is *not* turning.
3. "*Slipping*" or "*Spinning*": This occurs if all points of T in the contact patch have non-zero velocity relative to R even while the wheel rim is turning.
4. "*Stick-Slip*": This occurs if *some* of the points of T in the contact patch have *zero* velocity relative to R and the other points of T in the contact patch have non-zero velocity relative to R, and the wheel is turning.

Case 4) is of greatest interest in our analysis. It can occur with either braking or acceleration.

To explore this, consider a rapidly accelerating drive wheel as represented (in exaggerated form) in Fig. 9.

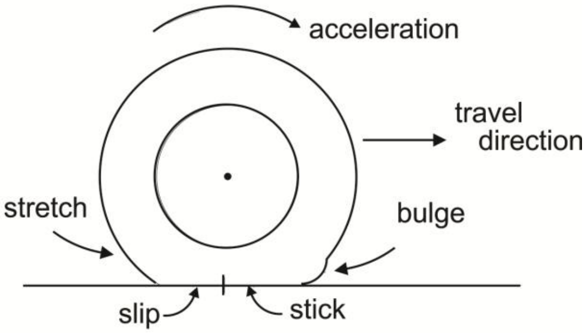

Fig. 9. A rapidly accelerating drive wheel

In the front of the tire near the roadway, the rubber will be in compression, and the tire will bulge. In the rear, the rubber will be in tension, and the tire will stretch. In the front portion of the contact patch, with the rubber in compression, the points of the tire will have zero velocity relative to the roadway (the "stick" region). In the rear of the contact patch, with the rubber in tension, the points of the tire will have non-zero velocity (slipping movement) relative to the roadway (the "slip" region).

Rapid braking produces a similar but opposite side stick-slip occurrence.

There are detectable physical evidences of these phenomena: When in the contact patch, as the tire surface passes from stick to slip, the rubber will begin to vibrate and slide on the roadway. The vibration produces the "squeal" (accelerating) or "screech" (braking) sound. The sliding often leaves visible skid marks on the roadway.

VI. Quick Braking in a Curve

Consider now a motorcycle rounding a curve, but on the verge of going out of control by sliding over the roadway toward the outside of the curve. Consider specifically the case with the vehicle *about* to go out of control, but *still in control* with both wheels rolling without slipping on the roadway.

Suppose next that the operator makes a firm, but brief, application of the rear wheel brake. In view of the foregoing analysis, with the braking causing a sudden deceleration of the rear wheel, there will occur compression (or bulging) in the rear of the wheel near the contact patch. Correspondingly there will occur tension (or stretching) in the front of the wheel near the contact patch. This in turn will promote tire slipping in the front of the contact patch.

With a portion of the tire slipping, the overall coefficient of friction between the rear wheel tire and the roadway will be reduced. The traction (or "grip") of the tire with the roadway will then be momentarily reduced allowing the rear wheel to slide toward the outside of the curve. But then, as the operator releases the rear wheel brake, the rear wheel will again be turning at a rate where there will be no bulging nor stretching of the tire. This means that the rear wheel will again be rotating at the pure rolling rate in the direction of travel.

Looking from above, this brief slide of the rear wheel toward the outside of the curve, say a curve to the left, will cause the motorcycle to be slightly turned counterclockwise, and redirected toward the center of the curve.

With the slight counterclockwise turn, the motorcycle wheels will be turned about a vertical axis. Then with the wheel rotation axes directed to the left, the wheels and vehicle frame will become more upright, according to the law of gyroscopes.

The slowing of the motorcycle due to the braking, the rolling without slipping of the rear wheel in the direction of travel, the redirection toward the center of the curve, and the vehicle becoming more upright, all contribute to reducing and eliminating an impending outward directed slide and loss of control. Specifically: the slowing reduces the outward directed inertia force ("centrifugal force"); the rear wheel rolling without slipping eliminates the bulging and stretching within the contact patch of the tire; the redirection toward the center of the curve contributes to the completion of the turn in the path of travel; and the vehicle becoming more upright places different and cooler tire tread on the roadway. Each of these provide the motorcycle operator with a greater measure of control.

Figs. 10 and 11 illustrate the steps of the procedure.

Table 1 Position Captions for Figs. 10 and 11

Position	Caption
A	Motorcyclist entering a curve at high speed.
B	Motorcyclist drifting to the outside of the curve.
C	Motorcyclist drifting onto the outside shoulder of the curve, leaning to the inside (Fig. 11) close to the critical slide angle θ_{cr} $\left(\theta_{cr} = \tan^{-1}\mu\right)$ (μ is coefficient of friction)
D	Sudden, firm rear wheel brake and slide of rear wheel to the outside of the curve.
E	Motorcycle redirected back onto the roadway and upright again.

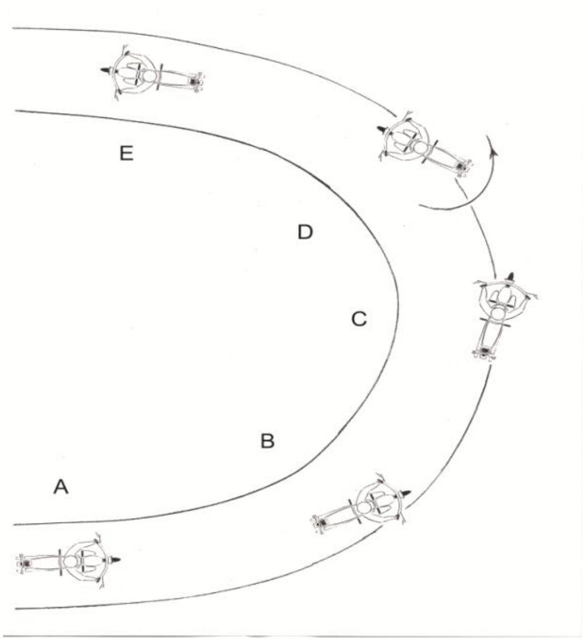

Fig. 10. Overhead view of motorcyclist travelling fast around a curve and then taking corrective action

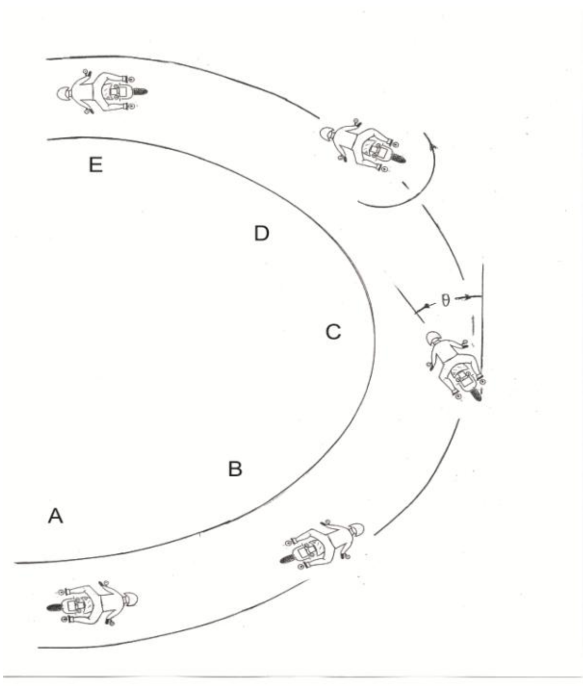

Fig. 11 Rear view of a motorcyclist travelling fast around a curve and then taking correction action

VII. TESTING AND VALIDATION

Our objective in the foregoing analyses is to provide theoretical bases for the motorcycle behavior. Although the motorcycle responses may be familiar for experienced operators, it is nevertheless still useful to test the predictions of the analyses.

To this end we (Schartman) tested a motorcycle's (1977 BMW RS100) response on a rural asphalt roadway. Without exception, the vehicle responded exactly as predicted: 1) a sudden (forward) push on the right (or alternatively, left) handlebar, caused the vehicle to go to the right (or left); and 2) the abrupt, but brief rear wheel braking, at high speed in a curve, reoriented the vehicle toward the center of the curve with a more upright configuration.

VIII. DISCUSSION AND CONCLUSIONS

Motorcycle popularity stems from three major motorcycle attributes: 1) enjoyable riding; 2) fuel efficiency in commuting; and 3) unique handling characteristics. "Unique handling" includes: rapid acceleration/deceleration (speed control); selective braking; quick lane change maneuverability, and sensitive control in turning.

These advantageous handling movements are made possible via multiple design features such as: 1) relatively light vehicle weight (as compare with an automobile); 2) direct manual steering; 3) independent front and rear wheel braking; 4) round profile tires; and 5) the gyroscopic effects of the wheels.

Of all these designs the gyroscopic wheel effects are paramount. In addition to keeping the vehicle erect (while moving) the gyroscopic effects work in conjunction with the steering, the brakes, and the round tires to enable the two control maneuvers discussed herein.

Of the two maneuvers, the quick turn is likely to be the easiest to master. Indeed, if an operator understands the maneuver, he or she can assist in the turning by simply leaning into the turn: To quickly turn right (or left), push forward on the right (or left) handle grip, and then lean to the right (or left).

The control recovery in a turn maneuver, however, is more delicate. Here the operator needs to get the vehicle to perform a mini rear wheel slide, much like a race car sliding around a curve on a dirt track. But this maneuver can also be mastered with practice.

Of the two maneuvers, the quick turn is relatively routine, whereas the curve control enhancement is mainly an emergency procedure.

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