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DESIGN OF A HUMAN-POWERED ROLL STABILIZATION ATTACHMENT FOR UTILITARIAN TWO-WHEELED VEHICLES

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ABSTRACT

This paper describes the motivation and development of a human-powered roll stabilization attachment for utilitarian two-wheeled vehicles. The proposed design has been built and tested by the authors in both on- and off-road conditions. It provides balance by providing a rolling platform underneath the two-wheeled vehicle (motorcycle) for the user to push against with their feet. This platform is placed under the driver's sitting position and is towed from a three degree-of-freedom joint behind the front axle (i.e. one of the implementations uses a ball hitch joint). Fifty eight percent of the world's motorcycles are in Asia Pacific, and Southern and Eastern Asia. In most of those countries, motorcycles greatly outnumber cars and many of these motorcycles function as utility vehicles. The uses of motorcycles include transportation of goods on the bike frame, transportation of goods on a trailer, and even pulling agricultural implements in farms. If no modifications are made to the motorcycle, at slow speeds operators of motorcycles must drag their feet on the ground and lightly push upwards as needed to retain balance. Attaching conventional outrigger wheels, similar to a motorcycle side-car, can negate some of the advantages of motorcycles that users value by: (A) preventing leaning into turns when rigid outriggers arms are used, (B) significantly increasing complexity and mass when outrigger arms mounted on suspension systems are used, and (C) increasing the vehicle's width such that it can no longer travel between car lanes or between rows of growing crop. An additional design consideration for balancing motorcycles is the user's need for quick conversion between a statically balanced vehicle and a vehicle can lean dynamically in turns, for example for someone who wishes to operate a motorcycle on farms but also travel quickly between agricultural fields. This conversion convenience is affected not only by the ease of attaching and detaching the balancing system but also by the ability to comfortably carry on the balancing system on the motorcycle even when it is not being used, such that it can be deployed when it is needed. This paper describes a design for a human-powered roll stabilization attachment that address these concerns and other identified user needs. It also provides with general equations to design similar human-powered roll stabilization systems for motorcycles.

NOMENCLATURE

$F =$ user applied force
$g =$ acceleration of gravity
$w =$ track width from motorcycle to one board wheel
$m_M =$ motorcycle mass (excl. balance board)
$H_M =$ height of motorcycle's CG

$\phi =$ lean of motorcycle
$m_R =$ mass of rider
$H_R =$ height of rider's CG
$\sigma =$ lean of rider
$a =$ distance rear axle to board axle
$L^* =$ distance rear axle to head tube
$r =$ rake of fork
$h =$ lateral distance from vehicle centerline to yaw (steering) pivot of balance board wheel
$j =$ lateral distance from yaw (steering) pivot of balance board wheel to balance board wheel when α is zero
$k =$ longitudinal distance from yaw (steering) pivot of balance board wheel to balance board wheel when α is zero
$c =$ longitudinal distance from lowermost point of motorcycle headtube to balance board yaw pivot
$\psi =$ steering angle of front wheel
$\alpha =$ steering angle of balance board wheel
$\theta =$ is the side slope angle
$V =$ vehicle speed
$T^* =$ effective track width
$R =$ radius of turn
$H =$ height of combined CG

1 Introduction - Motorcycles are ubiquitous and can be preferable to conventional four-wheeled vehicles or animal power.

Motorcycles are a relatively affordable motorized vehicle and, for most of the world's population, the most common motorized vehicle to own [1]. Approximately 80% of the world's motorcycles are in Asia - China and India alone have around 200 million motorcycles [1]. The number of motorcycles in the world is growing at a faster rate than that of cars [2]. The small dimensions and agility of motorcycles allow them to operate in situations and spaces where cars cannot [3]. The entry learning barrier to new users is lower for motorcycles than cars, particularly for users who can ride bicycles [3].

Modified motorcycles are an alternative to draft animals in agricultural areas that are difficult to access for four-wheeled vehicles, or where conventional farm tractors are too large or expensive [4] [5]. The majority of the world's farms are smaller than the conventional farm tractor was originally designed for [6]. Motorcycle ownership to enable working in transportation of people or goods have been associated with poverty alleviation in Africa and Southeast Asia [7] [8] [9]. Examples of motorcycles modified in India to be used as transportation vehicles or farm tractors are shown in Fig. 1. Motorcycles modified to have three wheels via a two-wheeled rigid rear axle can no longer lean on turns and must have their overall width increase beyond stock to achieve reasonable stability.

FIGURE 1. EXAMPLES OF MOTORCYCLES MODIFIED IN INDIA TO BE STATICALLY STABLE AND BE USED FOR TRANSPORTATION (TOP) AND FARMING (BOTTOM). Images by authors.

Roll stability of vehicles such as three wheeled motorcycles in Fig. 1 can be improved with mechanisms allowing roll leaning (referred to as tilting). This has been well studied and is a field of active work. Tilting can rely on passive mechanisms but better performance can be achieved with active tilt control. The best performance is achieved when both steering and tilt are actively computer controlled [10] [11]. Well designed three-wheelers with active stabilization systems achieve rollover limits in turns to within 20% of an equivalent track width four wheeled vehicle - which results in improved overall usability particularly for travelling longer distances on roads [12]. Improved safety of narrow three-wheeled vehicles with a specialized control mode that activates during abnormally aggressive turning maneuvers is discussed in [13].

The balance board design proposed in this paper is different than three-wheeled leaning vehicles in two ways: (I) It is intended to be a passive and mechanically simple system compatible with conventional two-wheeled motorcycle designs. This should enable it to be an accessible retro-fit component for existing motorcycles or a reasonable stock feature of specialized rural utility motorcycles costing under 1 Lakh (100,000) Indian

Rupees. This simplicity should also enable the balance board to be conveniently detachable/attachable to revert to a conventional motorcycle when that is preferable. (II) It depends on user physical effort to remain upright whenever a two-wheeled motorcycle would fall over. In contrast, three-wheeled leaning vehicles require little or no user effort to remain upright in their intended usage situations.

Designs to enable balancing a conventional two-wheeled motorcycle by adding two ground contact supports, as is done by the balance board in this paper, have been implemented in the past - such designs include: (A) Independent arms that attach to a rotation axis perpendicular to the vehicle's centerline near the front of the motorcycle frame and then extend rearward along the sides of the motorcycle to hold an idle wheel that has not no steering functionality. The user can press down on a foot platform on these arms to stabilize the motorcyce [14]. (B) Skis that articulate from the motorcycle and are nominally kept raised by weak springs, the user steps on the skis to lower them for stability in snowy or icy conditions [15]. This design has been used by Swedish security forces since the 1960s. The design still permits leaning in turns and depends on human force for roll stabilization. (C) Training wheels for motorcycles to make them safer and easier for children. Two additional wheels are attached rigidly to the sides of the motorcycle frame and always hold the motorcycle perpendicular to the ground, preventing it from leaning [16]. (D) Retractable motorcycle support wheels that are automatically lowered at low speeds (to keep the motorcycle perpendicular to the ground) and raised at higher speeds (to enable uncostrained leaning of the motorcycle [17].

2 Motorcycle dimensions are similar to bullocks and well-suited to small farmers in India

Relative to a conventional tractor, the bullock's compact dimensions, high maneuverability, and low capital cost have allowed them to remain the most common draft-generation source in Indian farms. Due to the tractor's lower ground clearance, larger width, and need of dedicated path for travel for many small farmers switching from bullocks to a conventional tractor would require adjusting crop spacing (particularly for crops taller than a tractor's ground clearance) and potentially even the access to their field. Compared to tractors, however, bullocks are slow at covering ground, incompatible with modern precision tools, and have higher ownership costs [5]. These obervations are supported by the authors' visits to India between 2014 and 2019 to speak with farmers and local experts.

Motorcycles, compared to tractors, are closer to bullocks in their dimensions and can fit between rows of tall crops and require small widths for turning. However, most farming operations are done below 4 km/h [18] [19] [20] which, compounded with the irregular field terrain, makes it difficult to balance on a conventional motorcycle. Typically this has required farmers to drag their feet on the ground to balance when riding at low speed. This is tiresome, allows an undesirable amount of roll, and can injure the toes of farmers wearing sandals. An existing alternative is to modify a motorcycle as shown in Fig. 1 but that negates most of the original advantages of a motorycle.

3 Overview of balance board implementation

To provide human-powered roll stabilization of the motorcycle, a design the authors are referring to as "balance board" was developed. This balance board design was implemented for testing on an all-wheel-drive, off-road motorcycle. The balance board provides a rolling platform under the motorcycle for the operator to place their feet on (Figs. 2 and 3). The balance board is attached via a ball hitch underneath the motorcycle frame and directly behind the front wheel. Nominally, therefore, the rotation of the balance board is independent of the motorcycle rotation for a large range of motion. When driving at slow speeds the motorcycle is unstable in the roll direction and may start to tip sideways. When side roll initiates, the user can press down on the balance board (which remains flat on the ground) with the leg towards which the motorcycle is tipping. This, in practice, has a very similar stabilization effect as pressing against the ground (as one would do without the balance board) but has two mayor advantages: (1) the reach to the balance board is much shorter than to the ground, allowing the driver to maintain a natural riding position; and (2) since the balance board is moving forward with the motorcycle, the rider is pressing down on a surface that is largely static relative to them (as opposed to dragging a foot on the ground or tip-toeing on the ground).

4 Force from user to balance motorcycle

Generally, the force required to correct motorcycle roll lean is small since the user intuitively balances by continually doing small corrections on small rotations rather than waiting for a large lean to act. The force required to correct for leaning varies non-linearly with the side-slope angle, the motorcycle's lean, and the driver's body position. It can be observed from Eq. 1 and Fig. 4 that the user's body lean can help correct for motorcycle roll leaning (lowering the magnitude of F in Eq. 1 even down to zero) if the sign of $(\sigma+\theta)$ is opposite of the sign of $(\phi+\theta)$. If the user and motorcycle lean together into the side slope the balancing force F can become zero in the ideal case where (σ) and (ϕ) are each equal and opposite to (θ) (i.e. (CG_{Moto}) and (CG_Rider) are both directly above (COR) in Fig. 4). An example of the rider and motorcycle leaning into the side slope to reduce force F is shown in image B of Fig. 10.

$$F = \frac{g}{w}\,(m_M\,H_M\,sin(\phi+\theta) + m_R\,H_R\,sin(\sigma+\theta)), \quad (1)$$

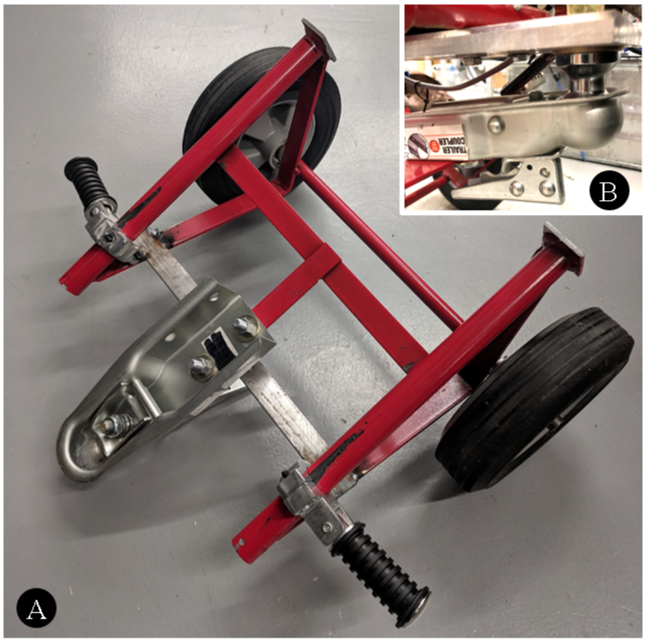

FIGURE 2. THE PROOF-OF-CONCEPT "BALANCE BOARD" AND ITS BALL HITCH ATTACHMENT TO THE MOTORCYCLE.

where, $F =$ user applied force , $g =$ is the acceleration of gravity, $w =$ is the distance parallel to the ground from the assumed center of rotation (COR) to the wheel of the balance board towards which the motorcycle is falling, $m_M =$ is the total mass of the motorcycle (excluding balance board), $H_M =$ distance from ground to the motorcycle's CG location when vehicle is parallel to gravity, $\phi =$ lean of vehicle relative to the ground normal, $m_R =$ is the total mass of the rider, $H_R =$ distance from ground to the rider's CG location when the vehicle and rider are parallel to gravity, $\sigma =$ is the lean of the rider relative to the ground normal, and $\theta =$ is the side slope angle.

5 Effect of turning on balance board effective dimensions

It has been found during testing that the motion of the balance board relative to the motorcycle during turning is an important design consideration for improving future iterations. The balance board wheels must steer in turns which results in effectively reducing the value of w in Eq. 1. This decrease in w then itself results in an increase of the user-generated force F required to keep the vehicle upright. In relatively fast turns this increase of Force F can be fully or nearly fully counter-acted by the inertial ("centrifugal") forces occuring at the motorcycle's and rider's CGs. However, in slower turns where the rider is leaning simply to induce a tighter turning radius this decrease in the value of w is detrimental to usability. In Fig. 8, image C shows how the foot on the inside of the turn is being swung towards the motorcycle centerline (effectively reducing w), image A shows how the balance board design currently implemented does not interfere with the user's ability to put their foot on the ground for very tight slow turns (as on a standard motorcycle) if that is their preference.

FIGURE 3. THE RIDER STEPS ON THE BALANCE BOARD TO PROVIDE SELF-POWERED ROLL STABILIZATION, ALLOWING THEM TO REMAIN UPRIGHT EVEN AT A STANDSTILL AND NAVIGATING UNEVEN TERRAIN SLOWLY.

Observations into the impact of balance board dimensions on how the balance board wheels move to steer during turns is provided by Eqs. 2-4 as well as Figs. 5, 6 and 7. In Fig. 5 Tire "A" demonstrates that placing balance board wheels longitudinally close to the rear axle will minimize the amount of turning they require. Tires "B" and "C" are progressively further from the back wheel and thus require larger turning angles. Tires "B" and "C" are connected via a rigid axial that rotates at its midpoint, to demonstrate the additional fore and aft motion that such an arrangement would result in. Eq. 4 is based on the dimension variables described in Fig. 6.

Equation 2 describes the longitudinal position from the in-

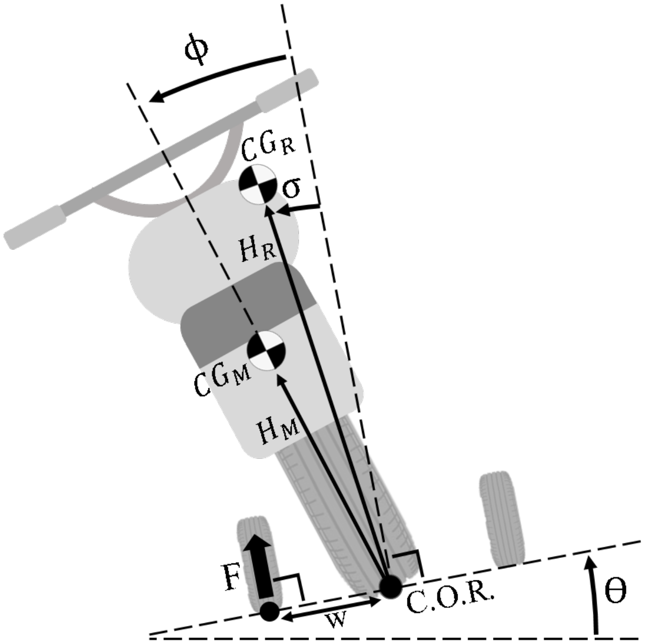

FIGURE 4. DEFINITION OF DIMENSION VARIABLES USED FOR CALCULATIONS OF USER FORCE REQUIRED TO PREVENT VEHICLE ROLLOVER.

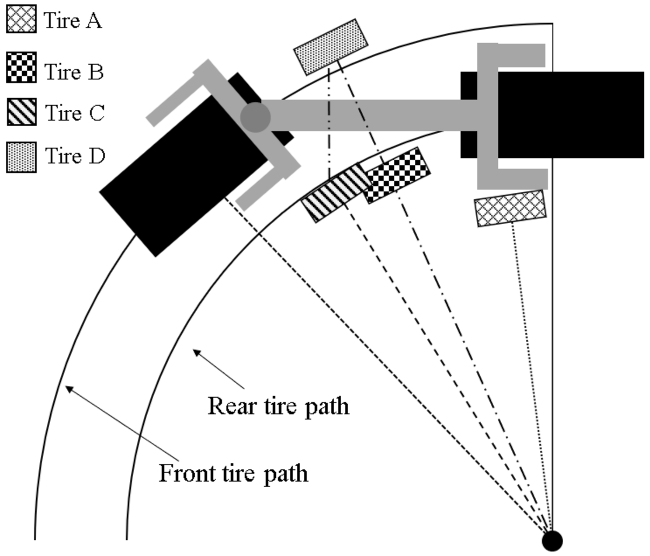

FIGURE 5. A SCHEMATIC OVERHEAD VIEW OF THE MOVEMENT OF THE INNER BALANCE BOARD WHEEL DURING TURNING.

side balance board wheel to the rear axle during slow turns where the motorcycle does not lean relative to the ground (distance *a*).

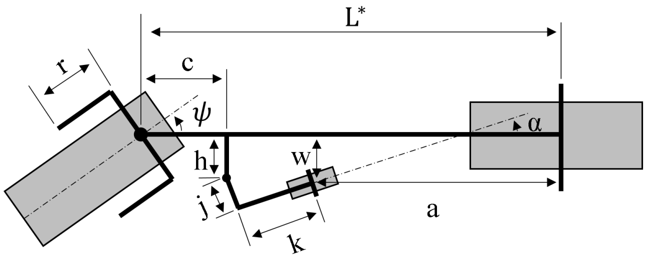

FIGURE 6. DEFINITION OF DIMENSION VARIABLES FOR MOUNTING OF BALANCE BOARD WHEELS DURING TURNS WHERE VEHICLE DOES NOT LEAN.

This scenario is expected to be important and common for the target users. Equation 2 is calculated by assuming the pivot between distances h and k has a vertical axis of rotation. To connect Eq. 2 to the implemented balance board design (where h=0) one must assume that since the motorcycle is operating on flat ground with no lean the ball joint is can be represented by a pin joint with a vertical axis (i.e. relative to the motorcycle the balance board will only have yaw rotation - no pitch or roll rotation is occurring).

$$a = L^* - c - \sqrt{j^2 + k^2}\, cos\left(tan^{-1}\left(\frac{k}{j}\right) - \alpha\right), \tag{2}$$

Equation 3 is calculated in the same manner as Eq. 2 but the distance being solved for is the lateral distance between the inside balance board wheel and the motorcycle centerline (distance w which is orthogonal to distance a from Eq. 2).

$$w = h + \sqrt{j^2 + k^2}\, sin\left(tan^{-1}\left(\frac{k}{j}\right) - \alpha\right), \tag{3}$$

Equation 4 is calculated from the geometric constraints shown in Fig. 5 and the kinematics of Fig. 6. Fig. 5 shows that in a zero slip turn with no leaning the projections from all wheel axles will intersect at the turn center. The steer angle of the balance board (angle *alpha*) must be such that it satisfies this constraint for a vehicle geometry as in Fig. 6.

$$\alpha = \frac{\pi}{2} - tan^{-1}\left(\frac{tan\left(\frac{\pi}{2} - \psi\right)\left(L^* + r\, cos(\psi)\right) sin(\psi) - w}{a}\right), \tag{4}$$

In Eqs. 2-4 a = distance from rear axle to inside outboard wheel axle, L^* = distance from rear axle to headtube lowermost point,

g = acceleration of gravity, r = rake of fork measured as distance from front axle to lowermost part of headtube, h = lateral distance from vehicle centerline to yaw (steering) pivot of balance board wheel, j = lateral distance from yaw (steering) pivot of balance board wheel to balance board wheel when α is zero, k = longitudinal distance from yaw (steering) pivot of balance board wheel to balance board wheel when α is zero, c = longitudinal distance from lowermost point of motorcycle headtube to balance board yaw pivot, ψ = steering angle of front wheel, α = steering angle of balance board wheel. Dimensions are overlayed on a simplified schematic vehicle in Fig. 6.

Figure 7 uses Eqs. 2-4 to show the change in w, a, and α during turning for a balance board with the dimensions of the implemented design (c=0.23 m, h=0 m, j=0.27 m, k=0.30 m). The dimensions of the implemented design were selected to match lateral position of the stock motorcycle pedals and yield an easy to manufacture proof-of-concept design. It is assumed that the vehicle is in steady-state slow speed turning (no vehicle leaning). Notice that for tighter turns (i.e. greater front wheel steer angle) the inside balance board wheel moves closer to the vehicle centerline (a smaller w) which increases balance force F in Eq. 1 and can slide the balance board foot support under the motorcycle frame in a critical cases (as is starting to occur in Fig. 8C). Since the balance board wheel axle is always parallel to the foot supports any changes in board steer angle α also cause the foot supports to rotate which affects the ergonomics of pressing on the foot pedal, which can be potentially uncomfortable for users operating barefoot or wearing soft soled sandals. Reducing the distance from the foot supports to the rear axle a can also affect ergonomics by making the user's knee angle more acute and placing their foot further under their hip. However, in this initial testing the range of a was not enough to be perceived as an issue by riders. It can be seen in Fig. 7 that the motion of a is not as large as the motion of w for reasonable steer angles ψ.

6 Discussion of observations from initial qualitative tests

The goal of this initial testing was to confirm the viability of the balance board concept as a tool for augmenting motorcycle usability at slow speeds, particularly in uneven, unpaved terrain. Drive testing included the following scenarios where the balance board performed satisfactorily. **(I) Turning (Fig. 8).** Turning at slow speeds with both feet on the balance board (a special feature of this system), as well as maintaining the ability to turning at slow speed while placing a foot on the ground and turning high speed while leaning (maneuvers that are possible on a stock motorcycle). **(II) Slow Speed Driving (Figs. 3 and 9).** Three situations were tested: gaining balance mounting the motorcycle at a standstill without initiating forward motion, driving at a walking speed in close quarters, and finally stopping to a full stand still while remaining upright. **(III) Driving on Uneven Terrain (Fig. 10).** Three driving situations were tested: driving up and down grassy pronounced slopes, driving along a slope (i.e. perpendicular to the slope gradient direction), and crossing sharp drop-offs of up about 20 cm.

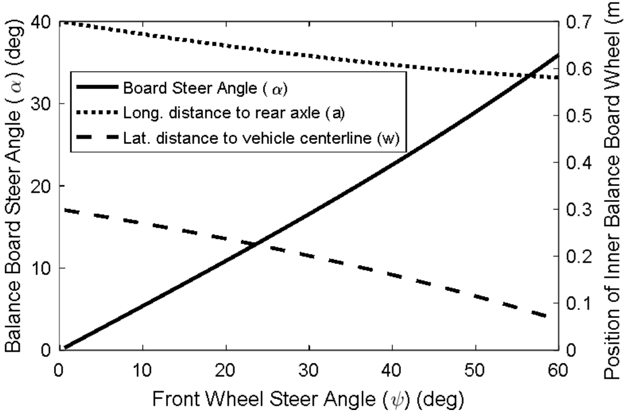

FIGURE 7. RELATION OF FRONT WHEEL STEER ANGLE (ψ) TO THE THE INSIDE BALANCE BOARD WHEEL POSITION AND ORIENTATION.

The balance board concept shows high potential as a viable intermediate option between motorcycles and statically stable vehicles (usually three wheelers or four wheelers). The balance board is no wider than the handlebars of the motorcycle and did not interfere significantly with the motorcycle accessing narrow spaces or performing maneuvers the stock motorcycle would have. It was comfortable to stop and restart without placing a foot on the ground as well as to ride slowly in close quarters on uneven terrain. Further testing in agricultural terrain and with instrumentation for motorcycle lean as well as user effort is needed and is planned for future research.

There are four major identified areas of opportunity in the current design. (I) The balance board moves the inside foot of the rider under the motorcycle during tight turning as seen in Fig. 8C. (II) The effective ground clearance of the motorcycle has been reduced compared to the stock vehicle, when the balance board wheels both roll over an elevated obstacles they cause their axle to rise and hit the motorcycle frame. (III) when the user first mounts the motorcycle at a stand still it can be hard to start balancing while remaining in place (i.e. without initiating forward motion of the motorcycle), once balance is found it is easy to maintain it, however. (IV) The current balance board wheels are significantly smaller diameter than the motorcycle wheels and the balance board frame reaches below its wheels' axle. Tall, narrow obstacles (like some rocks) will hit the balance board frame before they hit the balance board wheels which can be jarring for the rider.

All Wheel Drive Utility Motorcycle	
Base Vehicle	ROKON Scout
Mass	125kg
Mass supported by front wheel	60kg
Mass supported by rear wheel	65kg
Wheelbase	1.3m
Tire pressure	10psi
Tire model	TITAN 489XT
Tire size	12" rim, 8" wide, 25" diam.
Balance Board	
Mass	8kg
Overall width	0.6m
Distance mount to board axle	0.3m
Distance rear axle to mount	0.9m
Tire size	2" wide, 8" diam.

TABLE 1. BASIC DIMENSIONS FOR MOTORCYCLE AND BALANCE BOARD USED DURING TESTING.

FIGURE 8. IMAGES FROM TESTING THE VEHICLE IN DIFFERENT TURNING SITUATIONS. (A) Putting your foot down for an extremely tight turn, (B) Leaning during high-speed turns, and (C) Tight turns on slopes with both feet on the balance board.

7 Discussion: balance board design suggestions with alternative design for comparison

Based on the analysis in Sections 4 and 5 a few related design goals can be stated: To minimize balancing force F in Eq. 1, balance board width w should be increased to the limit permitted by the maximum allowable vehicle width. It is shown in Eq. 3 that balance board width w actually varies during turning, so to maintain w near the ideal maximum under most conditions the range of the second term in Eq. 3 must be minimized (the first term is a constant). This can be achieved by minimizing the values of balance board dimensions k and j as well as minimizing the range of balance board steering angle α. The balance board design must allow balance board steer angle α to equal zero during straight line driving - so minimizing the range of α is equivalent to always keeping it near zero. This can be achieved by minimizing the value of a in Eq. 4. The value of a can be made to exist only in a small range near zero by making $L^* \approx c$ and minimizing the value of j and k, as shown in Eq. 2. Simultaneously achieving all of these design goals may not always be practical when consideration is given to general ease-of-use, balance board wheel directional stability (which increases with k), and manufacturing costs.

FIGURE 9. EXAMPLES OF SLOW SPEED DRIVING IN TIGHT SPACES. (A) the vehicle travels between dirt mounds separated by 60 cm, the tightest crop spacing it is expected to operate in. (B) the motorcycle is driven at walking pace in a straight line.

The proof-of-concept balance board shown in Sections 3 and 6 is fully functional and has high potential to be a viable implementation. However, it is not a formally optimized design in dimensions or mechanical layout - that optimization is left for future work. For discussion of design challenges and freedoms in a balance board, an alternative design that makes $j = 0$ and minimizes k in a reasonably practical implementation is shown in Fig. 11. This alternative design replaces the ball hitch of the implemented design with four to five pin joints. Note that the distances j and k in Fig. 6 are measured from the balance board steering pivot (which is after the foot pedal in this alternative design). This alternative design has advantages and disadvantages compared to the implemented design, which will now be discussed.

Durability: The ball hitch connection on the implemented design is a simple and common joint. It is also a single joint, compared to the at least four joints in the conceptual design. Ad-

FIGURE 10. DEMONSTRATIONS OF THE BALANCE BOARD BEING OPERATED ON UNEVEN TERRAIN. (A) Steep uphill slopes, (B) side slopes, and (C) going down curbs in changing terrain.

ditionally, the caster joints in the conceptual design will see high radial forces due to them transferring a bending moment when the user presses down on the foot pedal.

Ground clearance: The implemented design is limited in its ground clearance for two main reasons: (1) the balance board frame rises when its wheels go over tall obstacles and hits the motorcycle frame, and (2) in tight turns the inside balance board wheel can swing under the motorcycle frame which further limits ground clearance. The conceptual design, on the other hand, does not change the stock motorcycles ground clearances when driving straight. During normal driving the caster wheels of the conceptual design will not reach under the motorcycle frame and thus ground clearance during turning also remains the same as the stock vehicle's.

Reversing: Most motorcycles cannot reverse under their own power, but doing so may become even more desirable with the additional slow speed utility the balance board can add. The implemented design is unstable when reversing. It behaves similar to a trailer towed with a ball hitch and will swing towards the motorcycle front wheel when reversing. Since the foot pedals are coupled to the implemented balance board wheels' steer angle, the user's feet will also swing with the balance board. The conceptual design can behave stably in both forward and reverse (the caster wheel will naturally steer 180deg when reversing to a new stable position). Since the foot pedals are independent of the conceptual balance board wheels' steer angle, the user's feet will remain in the same position whether moving forward or in reverse.

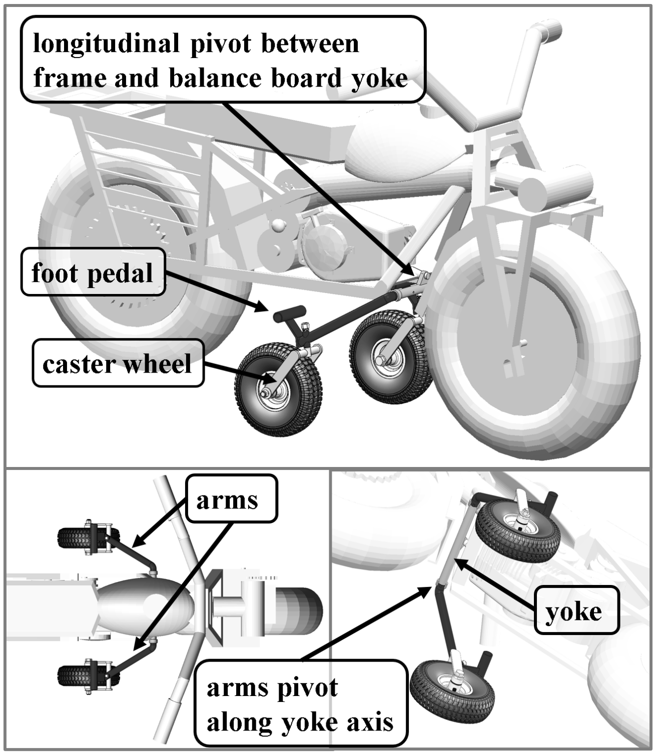

FIGURE 11. AN ALTERNATIVE BALANCE BOARD DESIGN CONCEPT ALSO CREATED BY THE AUTHORS. The two arms could be rigidly coupled to rotate together (four total pin joints) or independent (five total pin joints). In this paper, unless otherwise noted, the arms are assumed to be rigidly coupled.

Multi-purposefulness: The implemented balance board has the potential to serve as a small trailer if it is attached behind the rear wheel's motorcycle. It could carry a small water tank, for example. The conceptual balance board would not be useful for other activities. Both balance board designs are easy to remove, and are small and light enough to be carried on the motorcycle. When either balance board design is removed, the motorcycle can operate as it would as a stock vehicle.

Turning: During a turn, the wheels for both balance boards must reach a steer angle as represented in Figs. 5, 6, and 7. To achieve this steer angle, the implemented balance board must move along with its wheels. This motion will also carry the foot pedals and result in the user having to apply more force with on the foot pedal inside the turn to remain upright if such action is required (see Eqs. 1 and 3) as may be the case during slow, tight turns. As an alternative, the user can remove their inside foot from the foot pedal and press directly against the ground for balance as shown in Fig. 8A. In the conceptual balance board, the wheels can steer independently of the rest of the board and thus the user's feet will remain at a constant distance from the frame irrespective of the steer angle. This is advantageous if the user wishes to press on the foot pedal for balance but may also interfere with the user's foot path if they wish to place their foot directly on the ground for very tight turns (Fig. 8A). Placing a foot on the ground during large leaning into slow turns can be desirable since it allows a larger effective w in Eq. 1 (i.e. the rider's contact point with the ground can be extended out beyond the balance board).

Leaning in turns and side slopes: irrespective of the motorcycle lean (ϕ in Fig. 4), the implemented balance board remains parallel to the ground. When traversing side slopes, if the motorcycle remains nearly vertical then the down slope user foot will move downward and roll outward while the up slope foot does the opposite (see Fig. 10B). A small modification of the conceptual design can minimize foot roll on side slopes: if the longitudinal yoke pivot is blocked and instead the arms are allowed to pivot independently along the yoke axis (i.e. decouple the arms and prevent yoke rotation), then the conceptual balance boards foot pedals will remain parallel to the motorcycle rear wheel axle. On the other hand, while leaning in turns the modified conceptual design will force the rider's feet to lean with the motorcycle. In a typical use of placing the inside foot on the ground for balancing in a tight slow turn in a conventional motorcycle (without a balance board) the user's feet would be parallel to the ground, not the motorcycle. Keeping the feet parallel to the ground is also what occurs in the implemented balance board design and the unmodified conceptual design.

8 Conclusion

This paper has described the basic physics and two potential designs for providing human-powered roll stabilization to two-wheeled vehicles. One of the designs was implemented as a proof-of-concept and qualitatively tested. The designs are based on a wheeled "balance board" which is towed by the motorcycle and placed directly beneath the rider's natural feet positions. The motorcycle leaning is largely decoupled from the balance board's orientation. In this way the rider can balance themselves by pressing their feet downward against the board as needed - a similar method to placing or dragging a foot directly on the ground but with increased safety and comfort. Equations provided describe the balancing force the user must provide to remain upright under several slow speed operating conditions. Mathematical relationships are also established for how the balance board rider contact points move during turns - something that was found to be an important consideration for future designs during testing of the proof-of-concept balance board. Images and other qualitative observations from testing of the proof-of-concept balance board were also provided.

The theory and implementation observations described in this paper can be used to design low cost, mechanically simple human-powered roll stabilization systems for motorcycles. These systems could be relevant anywhere a motorcycle must be able to operate slowly (walking pace or slower) continually but still be able to maintain small overall dimensions, high maneuverability, and the ability to lean in turns at high speeds. Applications with those requirements, for example, are agricultural field work and motorcycle police that patrol pedestrian areas.

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