Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2011
August 28-31, 2011, Washington, DC, USA

DETC2011-47963

A REVIEW ON HANDLING ASPECTS IN BICYCLE AND MOTORCYCLE CONTROL

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ABSTRACT

This paper gives an overview on handling aspects in bicycle and motorcycle control, from both theoretical and experimental points of view. Parallels are drawn with the literature on aircraft handling. The paper concludes with the open ends and promising directions for future work in the field of handling and control of single track vehicles.

1 INTRODUCTION

The current upsurge in cycling worldwide is a result of many environmental and social changes that have taken place in recent years. These changes include the large scale governmental promotion of the bicycle as an environmentally friendly mode of transportation, infrastructure improvements and the spectacular increase in fuel prices making commuters think twice about their daily trip to the office. Not only the standard bicycle has profited from the upsurge, also many new sectors have been explored for the bicycle such as cargo bicycles for transporting goods and children, recumbents for long distance commuting, and foldable bicycles for multi-mode transportation solutions.

The development of the bicycle was an evolutionary process as described in [21] and shown in Fig. 1. Started early in the nineteenth century as a walking machine or velocipede (initially with a vertical steering axis), the bicycle transitioned through a period as a high-wheeler for greater speed but decreased longitudinal stability, to eventually evolve into the standard 'safety' bicycle by the end of the nineteenth century. This evolutionary process, based on trial and error, took about 80 years to finally come to the bicycle design which is still in use today. Since 1900 the bicycle has been optimized further, however most of these optimizations were cosmetic.

With the recent rapid increase in popularity of non-standard bicycles, many new designs are being developed by manufacturers to fill the gaps in the market. Therefore once again a new trial and error based evolutionary process appears to have begun. It seems strange that in a time when every flying quality aspect of a highly advanced and sophisticated aircraft can be predicted and designed a-priori its production, that the bicycle, as simple and elegant as it is, is still designed and built based purely on trial and error and the manufacturers experience. It should be possible, just like in the aircraft and automotive industry, to predict the handling qualities of bicycles, based on models of the rider and vehicle. Therefore it should also be possible to eliminate the trial and error from the process of reaching an optimum design for these new non-standard bicycles.

This paper aims to provide a review of research efforts that have gone into the handling of bicycles and motorcycles, the so called single track vehicles. The modeling and experimental validation of the rider control is not considered here and left for future study. This paper starts with some of the most important work in the field of single track vehicle models and their experimental validation before the definitions of concepts such as handling qualities and maneuverability are reviewed. The paper concludes with open ends and promising directions for future

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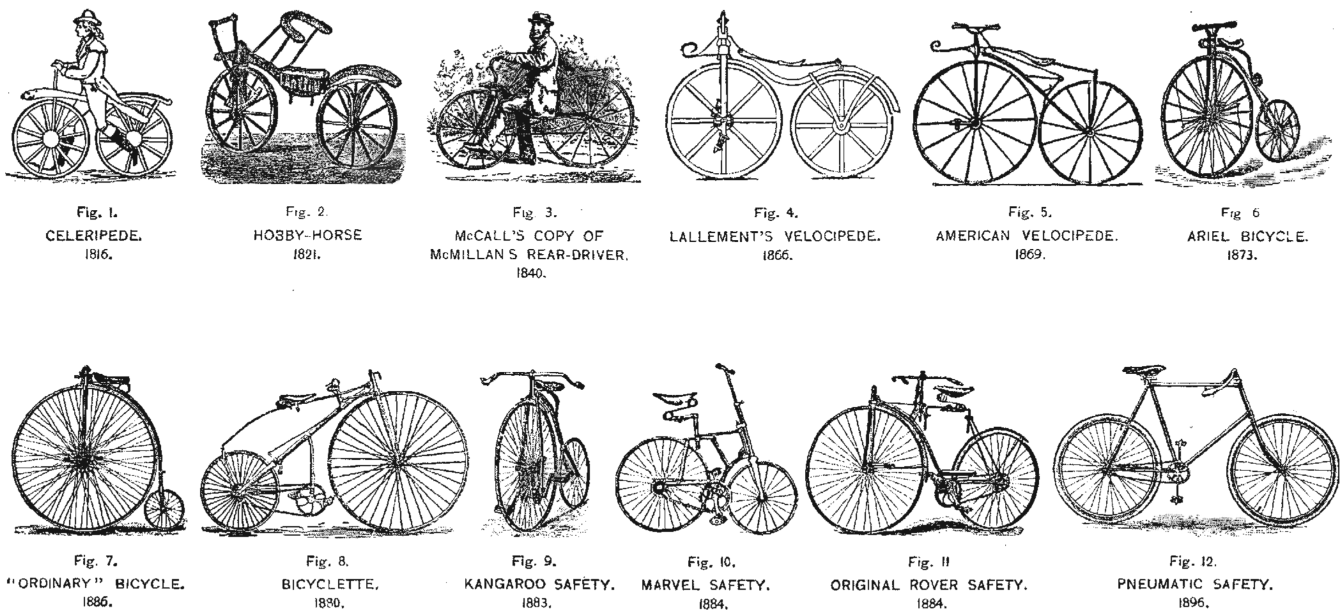

FIGURE 1. THE EVOLUTION OF THE BICYCLE FROM VELOCIPEDE TO SAFETY BICYCLE, FROM 'THE AERONAUTICAL ANNUAL 1896' [31]

work in the field of handling of single track vehicles.

2 DYNAMICS OF SINGLE-TRACK-VEHICLES, MODELING AND EXPERIMENTS

There have been a number of review papers on the subject of the dynamics of single-track-vehicles. Notably *Meijaard et al.* [32] carried out a comprehensive review on all those that investigated bicycle dynamics. *Sharp* [49] recently reviewed the dynamics and control of bicycles and earlier on motorcycle steering behavior [48]. In this paper we will only present some of the highlights.

As early as 1869 [39] it was already noted that a bicycle and rider in forward motion balance by steering towards a fall. By 1899 *Carvallo* [5] and *Whipple* [54], independently of one and other, were the first to develop the equations of motion for a bicycle with which they could predict instability modes. In the following one hundred years over fifty other authors independently modeled the bicycle until in 2007 *Meijaard et al.* [32], benchmarked Whipple's bicycle model and compared them all to this.

The first to develop and report fully correct equations of motion for a motorcycle was *Döhring* [13] in 1953. He also carried out experiments with a motorcycle to validate his model. His model was essentially the same as that of *Whipple* [54] and did not take tires or suspension into account. The first to investigate the motorcycle's stability using a proper tire model was *Sharp* [47]. Since then practically all research into single track vehicle dynamics and modeling has been focussed on motorcycles, for a review see *Popov et al.* [37].

The most significant (complete) multi-year, multi researcher scientific program focussed on single track vehicle stability and control was carried out in the 1970s by the Cornel Aeronautical Laboratory (later renamed Calspan). Much of the work on bicycles however was carried out for the Schwinn Bicycle Company and has only just become publicly available. They both modeled and experimentally measured bicycles and motorcycles (with tires) [46, 40] and their control [45, 43], comparing experimental maneuvers to time series simulations with the computer. This was quite a feat considering the computer system technology available in the 70's.

Measuring bicycle and motorcycle parameters, in particular measuring mass moments of inertia, has been done in a similar manner to Döhring, by either using a rotational accelerating platform or a torsional pendulum [46, 14, 38, 28]. For the recording of data during experiments Döhring installed a roll-chart recorder on the front frame of the test motorcycle, whilst an ingenious boom system was used at Calspan to relay the measured signals of the wired sensors on the bicycle via cables to large multi-channel strip chart recorders that were placed in a chase car. This method was also used by *Eaton* [14] to carry out experiments to validate the motorcycle model developed by *Sharp* [47] and theoretical rider control and motorcycle handling work by *Weir* [53]. With modern electronics measuring equipment has become far more compact. *Kooijman et al.* [28] placed all the required measuring equipment (power supply, sensors,

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digital to analogue converter and laptop computer) on a bicycle to experimentally validated the benchmark bicycle model [32] for a range of speeds. To measure the dynamics of a bicycle moving forward in its stable speed range requires the bicycle to be perturbed. *Roland & Massing* [46] at Calspan developed an interesting method for applying a known lateral (perturbation) force to the bicycle: a calibrated fireworks style rocket attached to the bicycle!

Recent experimental investigations into the benchmarked bicycle model [32] include: *Stevens* [50] who validated the model for a wide variety of bicycle geometries using a variable geometry bicycle and *Kooijman et al.* [25] who used the theory developed for the benchmark bicycle model to design and experimentally test a "two mass skate" bicycle that is self-stable without gyroscopic or caster effects. *Tak et al.* [51] investigated both theoretically and experimentally the effect of various parameters on the stability of a bicycle while *Moore et al.* [34] comprehensively measured the parameters of six common bicycles to compare their uncontrolled stability based on the linearized equations of motion. In order to carry out rider control experiments on a treadmill *Kooijman & Schwab* [27] experimentally investigated the dynamics of the uncontrolled bicycle on the same treadmill using the bicycle with which they had previously validated the benchmark bicycle model [28].

3 HANDLING QUALITIES: STABILITY AND MANEUVERABILITY

In Tony Foale's book entitled 'Motorcycle Handling and Chassis Design' [15] 'handling' is defined as "the ease, style and feel with which the motorcycle does our bidding". This definition, is in no way precise at it can be interpreted in a multiple of manners, yet seems to describe the thoughts that many have about the term 'handling'.

For engineering based definitions we first look at the aircraft industry which obviously have had most to profit from research on handling qualities and thus it is not surprising that this is also where most of the insight initially was developed. *Cooper & Harper* [6] were the first to precisely define what they mean by handling qualities of aircraft, namely: "Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role". Where they defined 'task' as "the actual work assigned to a pilot to be performed in completion of or as representative of a designated flight segment" and 'role' as "the function or purpose that defines the primary use of an aircraft".

Cooper & Harper state that both physical and mental workload need to be taken into account when rating a handling quality. They argue that a pilot can perform specific maneuvers just as well in very differently behaving aircraft and that the measurable physical workload can be identical but that the mental workload can be very different. They therefore developed a 10 scale pilot rating system (shown in Fig. 2) for determining aircraft handling qualities which became the norm for the industry and beyond. This rating system takes the mental workload into account.

However correlations have also been found indicating that handling qualities can be linked directly to control effort. *McRuer & Jex* [30], and *Hess* [22] found that the pilots perception of the task difficulty and therefore of vehicle handling qualities, are highly correlated to the 'power' of the pilot's output-rate feedback signal. They therefore only look at the physical workload and use it to define the handling qualities. This changes handling qualities to a control feedback problem. They found that the complete closed loop system wants to act as a first order system (with a 20 dB/decade drop off in a Bode plot) around the cross over frequency (the frequency above which the transfer function magnitude becomes smaller than 1) and where the desired band width (the frequency at which the cross over frequency occurs) is achieved by the pilots control effort.

Substantial research on motorcycle handling, mostly based on rider control effort, has been performed by Cossalter (see sections 3.2 and 3.3). Yet he [7] also stresses that the rider's subjective interpretation determines the handling qualities of the vehicle. He points out that this subjective rating depends on the rider's driving style and sensitivity, and on the motorcycle's response to lateral acceleration and yaw rate, sideslip, sensitivity to external disturbances, response to control actions under different circumstances, and the feedback between rider and motorcycle. Thereby making handling qualities both a rider and vehicle attribute where, similar to Cooper & Harper, both the rider's physical and mental workload are factors. *Foale* [15] similarly says that motorcycle handling characteristics depend largely on motorcycle parameters: the overall geometry, chassis stiffness, weight and its distribution, tyre type and size, but also on the rider's 'responses', which again indicates both mental and physical workload.

The most significant difference between aircraft and bicycles and motorcycles with regard to designing for handling qualities, is their ratio of pilot/rider to vehicle mass. The mass of a motorcycle rider is usually around 50% of the total mass while for bicycles the rider can be as much as 90% of the total mass. On the other hand, for a fighter aircraft the pilot mass is typically less than 1% of the maximum takeoff weight. The influence of the mass distribution on the open loop dynamics of a bicycle was shown in [25]. They developed a bicycle which has no caster trail and no net angular spin momentum yet is self stable due to the specific mass distribution used. Furthermore they showed that the self stable speed region of a bicycle can completely be eliminated by adjusting only the mass distribution of the front frame [26].

Any motions executed by an aircraft pilot that do not disturb the control stick or rudder pedals will have little to no effect on the aircrafts trajectory, whilst for a bicycle or motorcycle the body motions that do not disturb the handlebars directly can still

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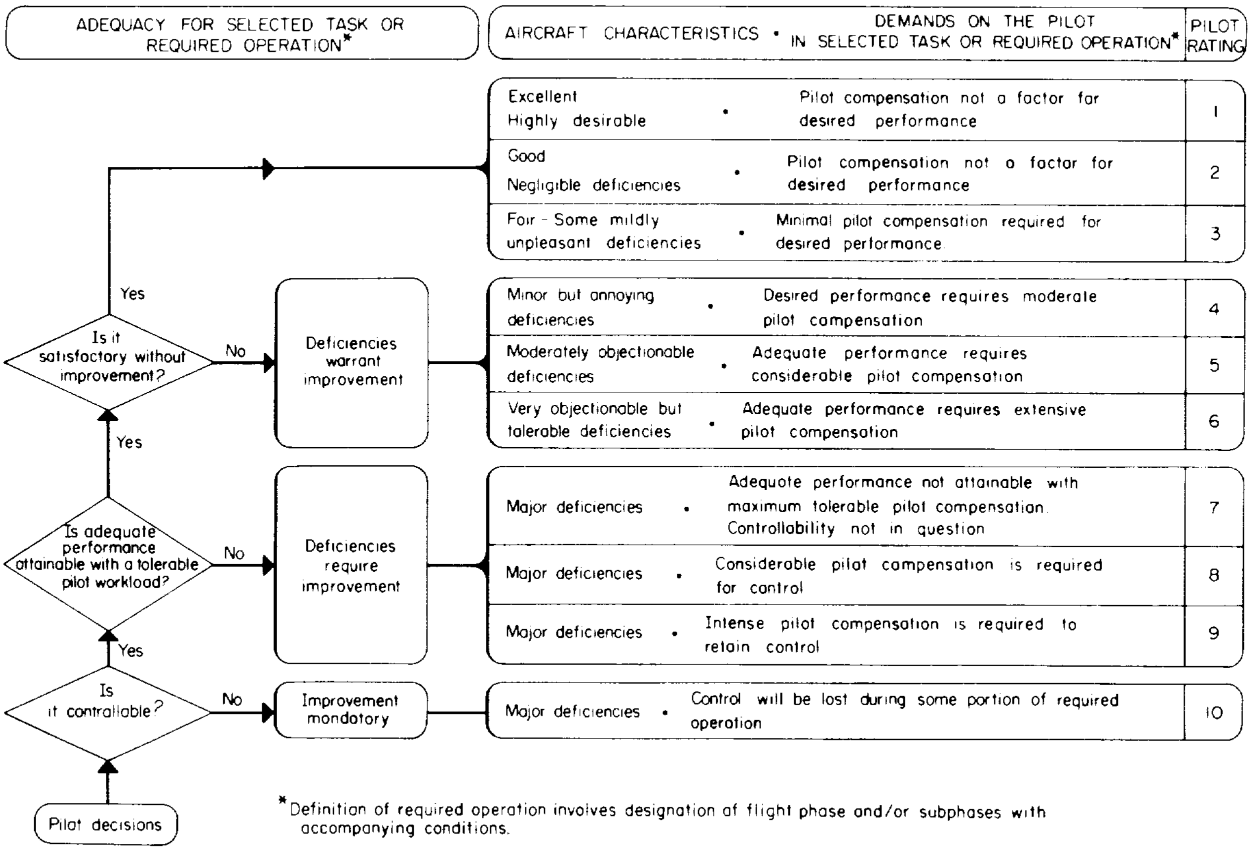

FIGURE 2. THE COOPER-HARPER HANDLING QUALITIES RATING SCALE, FROM [6]

cause a trajectory change of the bike as a result of the lean to steer coupling and relatively large mass of the rider. Examples of how the control strategy influences the trajectory of the vehicle, enabling different riders to complete the same maneuver in different ways were shown by *Cossalter* [7] for a U-turn maneuver and *Rice* [41] for a steady turn and for a lane change maneuver. Rice found large differences in control strategies performed by novice and skilled riders. Both Rice and Cossalter concluded that a rider on a motorcycle can successfully carry out a specific maneuver in many different ways. This indicates the difficulties that arise in modeling rider control but also that experimental tests can be performed in different ways by riders, making the comparison of subjective handling evaluations difficult.

Bicycle and motorcycle designers can however only develop the machine part of the complete machine-rider system. They design their machine generally for the following roles:

- accident avoidance maneuvers: safety aspects
- normal riding: the safe use in and amongst traffic whilst obeying the traffic rules
- racing: the completion of a lap around a circuit in the shortest time possible

The first role is in aircraft terms more a 'segment' of the 'designated flight plan' for which the designers want to achieve maximum performance in under all circumstances. This role has (logically) received most of the attention. The last two roles generally lead to very different looking vehicles, largely as a result of ergonomic and aerodynamic aspects. The next sections discuss these three roles in order.

3.1 Handling Qualities For Accident Avoidance: Safety

This section will first discuss the research on bicycles then on motorcycles and close with a discussion.

3.1.1 Bicycles Generally bicycle riders do not wear a helmet or any other protective clothing making them the most vulnerable of all road users. This may explain why most of the research into handling qualities for accident avoidance has been on bicycles. Most of the work has been experimental where both the rider skill and the vehicle attributes were tested simultaneously. Many of the experiments used to investigate the effect of

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different parameters on two general aspects, namely 'maneuverability' and 'stability' are listed in Tab. 1.

Rice, Roland and *Lynch* [44,45] are among the first to investigate the lateral stability and control of two types of bicycle that were popular in the late 1960s and early 1970s. They investigated the effect of nine parameter changes on the same instrumented bicycle (load on the rear, the rider and the front, increasing the mass moment of inertia of the front wheel and under-inflating the tires) for four experiments (straight line, obstacle avoidance and a narrow and wide slalom). They concluded that the standard bicycle is the best and that load in the rear placed low is good for 'maneuverability' whilst load on the rear placed high is bad for 'maneuverability'.

The effect of different style handlebars (high rise, standard and racing) on the 'maneuverability' of the bicycle was experimentally investigated by *Mortimer et al.* [35]. Riders carried out seven experiments and rated each bicycle and each task on a five point scale. They concluded that "since the high rise handlebar configuration allowed good maneuvering performance it should be considered an acceptable design. Standard handlebars offer a good compromise between the characteristics of the racing and high rise types, and provided stable, low speed tracking which is important for safe riding on streets in the mix of other traffic."

Godthelp, Buist and *Wouters* [18, 19] developed a bicycle with which they could change geometric parameters such as the wheelbase, trail, and moments of inertia of front frame and wheels, and carried out four experiments in each configuration (see Tab. 1). They also carried out these experiments with four different style bicycles and mopeds and concluded that all bicycles have the same 'high speed stability'. For low speed 'stability and maneuverability' they concluded that the rider position is dominant and that the racing bicycle and the high-rise handlebar bicycle were the worst.

The effect of different riding positions and bicycle styles on a child's ability to control a bicycle safely in traffic was investigated by *Arnberg & Tyden* [1]. Using time as a performance measure they measured the 'stability' and 'maneuverability' of six different bicycles in ten experiments where the bicycles were controlled by children (three bicycle styles (normal, foldable and rodeo) and two types of handlebar (normal and high rise)). They, similarly to *Mortimer et al.* [35] concluded that bicycles with extreme handlebars have a poorer 'maneuverability' performance than those with standard handlebars and that the race handlebars make the bicycle least 'maneuverable' whilst high rise handlebars are okay. Also similarly to *Roland & Lynch* [45], they concluded that the Rodeo style bicycle (mass high and to the rear) has the worst maneuverability performance out of the three tested models.

Similar safety experiments with young children were carried out by *Wierda, Roos & Wolf* [55, 56] to investigate 'maneuverability'. However time was not a measure in their experiments instead they only recorded errors made as they view 'safety' completely from the traffic point of view: to safely ride on the roads, the rider should be able to carry out the specified maneuver in a specific section of the road as any deviations could result in contact with another road user. They however concluded interestingly enough, that there are no major differences in 'maneuverability' between the different bicycle styles for children.

3.1.2 Motorcycles

The 'maneuverability' of a motorcycle and automobile was experimentally compared by *Watanabe & Yoshida* [52] by carrying out the same evasive maneuver with the motorcycle and car. They found that the motorcycle required significantly longer evasive distances than the car, despite the car being much wider than the motorcycle. They also found that less skilled riders require 15 to 20% more distance to avoid the obstacle than skilled riders. Furthermore speed has less influence on the performance of skilled riders than unskilled riders who seemed unable to produce large steer-torques at higher speeds. They concluded that for motorcycles riding at speeds above 30 km/h they would consider 'maneuvering' around an object instead of attempting to stop before it as the better evasive 'maneuver' due to the distance to speed relationship that the 'maneuver' has whilst stopping has a distance to speed^2 relationship.

The large research program carried out at Calspan (originally Cornell Aeronautical Laboratory or CAL) in the 1970s included exploratory research into accident avoiding capabilities of motorcycles by *Rice, Davis & Kunkel* [42]. To investigate the directional stability and control of motorcycles they developed a transient (single lane change) and steady state (constant speed variable radius) maneuver to evaluate the input-output relationships. The single lane change maneuver has been used by many other authors since. They modeled 6 motorcycles (including all geometric and inertial parameters, tires (which they also measured) and rider control) and carried out experimental validation tests with one. With these modeled motorcycles they tried to identify machine physical properties on performance measures for accident avoidance. They concluded that substantial differences in values for several performance parameters could be shown amongst the various motorcycle designs and that tire performance characteristics were very important.

3.1.3 Safety discussion

Most safety related handling qualities work has been on bicycles and of experimental nature where the complete system, bicycle and rider, were tested simultaneously. No standard tests were used, making direct quantitative comparisons between experiments impossible. Furthermore all the experimental ratings listed above are comparative, using relative scales and vehicle/rider combinations. Therefore within a single study vehicles and vehicle properties can be compared, but this is not possible between studies as they are not universal. Also none followed the Cooper-Harper methodology whereby the physical and mental workload is measured separately. Most

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TABLE 1. BICYCLE MANEUVERABILITY AND STABILITY EXPERIMENTS AND HOW THE PERFORMANCE IS RATED

Term	Authors	Experiment	Performance Measure
'Maneuverability'	Mortimer, Domas, Dewar [35]	Slalom at 5, 8, 10 and 12 mph and max speed	Crossing boundary and cones, max speed
	Arnberg, Tyden [1]	Block slalom, block pairs, 1 handed curve, 'relay' riding and steady-state circle	Time + interview
	Godthelp, Buist [18] Godthelp, Wouters [19]	Complex slalom	Time
'Performance'	Rice, Roland [44]	Slalom	Minimum time
'Control'	Roland, Lynch [45]	Slalom	Max speed
	Mortimer, Domas, Dewar [35]	Circle, figure-eight, lane change	Time
		10 mph, 90° corner	Minimum radius
	Arnberg, Tyden [1]	Stationary balance, ride between 2 narrow gates: a) constant speed, b) accelerate from rest	Time + interview
High speed 'stability & maneuverability'	Godthelp, Buist [18] Godthelp, Wouters [19]	Straight + corner with either left, right or both hands on handlebars	Time
Medium/High speed 'stability'	Mortimer, Domas, Dewar [35]	Straight between two lines	Boundary crossings
	Arnberg, Tyden [1]	Looking backwards over shoulder for a number	Boundary crossing, recalling number
	Godthelp, Buist [18] Godthelp, Wouters [19]	Straight between two lines	Relative time between lines
Low speed 'stability'	Rice, Roland [44]	Hands free straight ahead	Minimum speed
	Roland, Lynch [45]	Straight line hands on	Minimum speed
	Mortimer, Domas, Dewar [35]	Straight between two lines	Boundary crossings
	Arnberg, Tyden [1]	Straight between two lines	Time + interview
	Godthelp, Buist [18] Godthelp, Wouters [19]	Straight between two lines	Relative time between lines

did not even interview the rider to get an indication of the mental workload level.

None of the studies actually define what they exactly mean by terms like 'stability' and 'maneuverability'. However from the above it does appear that most authors refer to 'stability' within the framework of 'safety' as the ability of the bicycle and rider system to remain upright and within a narrow straight path. Stability is measured in terms of deviations from that path or by the minimum speed that the maneuver can be carried out at. The term 'maneuverability' usually refers to the system's ability to change direction, such as in a slalom or lane change. A more 'maneuverable' vehicle can carry out the same maneuver at a higher speed (slalom) or in a shorter time/distance (lane change). The maneuverability of vehicles appears to largely depend on two factors: the mass distribution of the system, in particular the riders location and orientation (mass moments of inertia) and the style of the handlebars and thus the riders ergonomics.

3.2 Handling Qualities For Normal Riding

Normal riding refers to the majority of a vehicles usage on open roads: not under extreme circumstances or at the performance limits. The majority of the work on this role has been carried out on motorcycles. However we start with three bicycle studies.

Relatively unknown is the work by *Herfkens* [20] who analytically investigated the effect of bicycle parameter changes on self-stability under the assumption that self-stability is a positive aspect for handling qualities. Interesting is his conclusion that the inertia of the steering assembly (including the wheel) should not become too low, is in stark contrast to what has been the main goal of bicycle and component manufacturers who have been introducing carbon composite components to reduce the weight of the bicycle as far as possible.

The work by *Jones* [23] from 1970 is by far the best known paper on bicycle stability or self-stability. It was even reprinted

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in 2006 by Physics Today as one of their classics. Jones experimentally investigated the 'stability' of the bicycle with and without rider. He performed physical experiments with bicycles with adjusted parameters to rate them as rideable or un-rideable. Jones investigated the effect of the gyroscopic action of the front wheel and found that it didn't have a major impact on the 'feel' of the bicycle. He then discovered that trail was the major factor in determining self stability of his test bicycle and introduced a 'stability index' based on the change in height of the front frame center of mass with respect to the steer angle. This stability index is still widely used today, including by reputable magazines carrying out product evaluation "tests". However the theory behind this stability index has recently been shown to be incorrect (or at least incomplete) and it has been shown that this stability index does not predict self-stability [25, 33] .

The work by *Patterson* [36] on bicycle handling qualities is also relatively well known. It introduced three relationships with which Patterson claims to be able to predict handling qualities of bicycles. 'Roll authority', being the relationship between steering angle and roll[1] rate, 'yaw authority' the relationship between steering angle and yaw rate and thirdly 'fork flop' the steer torque to keep the steer angle zero when a stationary (forward speed is zero) bicycle is leaned sideways. Each of the relationships is calculated using static (forward speed is zero) models by Patterson, therefore the correctness of the calculations is in serious doubt.

More research has been done for motorcycles. *Foale* [15] reports on experiments carried out on a BMW R75/5 motorcycle with various head angles and trail. His conclusion, which is in contrast to that of Jones and Patterson, is that there is nothing magical about currently used values (72° head angle and 9 cm trail), almost any positive trail and head angle is rideable, even given some moderate forward speed with hands-off.

Incidentally both Foale and Patterson note the importance of rider proprioceptive feedback. Foale points out that this sensory mechanism is used by the rider to determine the level (extreme) of breaking and cornering, whilst Patterson claims 'fork flop' to be essential in bicycle design as it gives good proprioceptive feedback to the rider.

Analytically the influence of the dominance of rider mass was investigated by comparing the lateral dynamics of mopeds (small mass) and motorcycles (large mass) by *Zellner & Weir* [59]. They concluded that the moped is more sensitive than the motorcycle for steer torque control yet the required rider lean input is (surprisingly) the same for the motorcycle and much lighter moped. Based on this research they gave design improvement suggestions.

Most motorcycle research though has been focussed on developing test maneuvers and handling indexes, and correlating experimental results with simulation results.

To rate different maneuvering aspects, such as steady state and transient behavior in separate maneuvers, five tests have been defined: steady turning, U-turn, slalom, lane change, and obstacle avoidance test [43, 7]. For each test, handling indexes have been developed, these are described in Tab.2. The Lane change maneuver has received most attention from researchers.

The 'Koch index' [24] was defined to classify the ease with which a turn is entered (transient response) by relating the peak in steer torque to the first opposing peak in roll rate. Later the 'lane change roll index' (LC index) [12] was defined to classify the transient lane change maneuver by relating the peak to peak rider input steering torque to the peak to peak roll rate of the motorcycle. Both indexes are normalized by the forward speed. These handling indexes have been found to correspond well with what is perceived as 'good handling' [7].

The LC index was shown to be an objective function for comparing motorcycles [12], and in the same study it was shown with an analytic approximation of the LC index that motorcycle 'maneuverability' is dominated by front wheel inertia properties. This is in contrast to what Jones had found for the far lighter and slower moving bicycle.

Prior to the introduction of the LC index the lane change performance was shown in 'performance maps' by *Rice* [41], these are the loci (*xy*-plot) of the steer torque and roll angle (the quotient of which is the Roll Factor). With these plots Rice was able to distinguish between successful and unsuccessful maneuvers and different riders.

Lane change maneuvers with motorcycles were simulated and carried out experimentally by *Rice & Kunkel* [43] and *Zellner & Weir* [58]. The latter also developed a steady-state turn maneuver procedure and used the Roll Factor and Yaw Factors to compare experiments with analytic simulations for five different motorcycles with mixed success.

The 'perceived steering effort' was investigated by *Kuroiwa et al.* [29] for a lane change maneuver. They note that the (counter-)steer action is perceived by the rider as a downwards and forward push of the hand on the side of the handlebars that the rider wishes to turn to. Therefore there they say there is a strong coupling (which they also find experimentally) between steer torque (τ_S) and the torque applied in the perpendicular direction - the so called 'roll steer torque' (τ_R). The roll steer torque may not influence the movement of the motorcycle but it is considered as it may relate to the riders perception. They measured these torques in two situations, first by rotating the handlebars on a vertically clamped stationary motorcycle while keeping the rider's upper body vertical (peak values are τ_{S1} and τ_{R1}) and secondly during a lane change maneuver (peak values are τ and τ_{R2}). They calculate the 'rider control torque' τ_{RC} (see Tab. 2) which they say corresponds to the increment of the steer-roll torque (τ_R) caused by the rider's upper body movement between the stationary and dynamic measurements. They find that for the motor-

[1]Where roll angle is the rotation about the longitudinal axis of the bicycle, and part of the yaw-pitch-roll orientation system as commonly used in vehicle dynamics. In the benchmark bicycle [32] this bicycle roll angle is called the lean angle of the rear frame.

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TABLE 2. MANEUVERS USED FOR RATING MOTORCYCLE HANDLING, THE INDEXES USED TO RATE THEM AND THE CORRESPONDING VALUES FOR GOOD HANDLING ACCORDING TO [7, 12, 24, 29]. WHERE τ IS STEER TORQUE, φ ROLL ANGLE, ψ YAW ANGLE, δ STEER ANGLE, V FORWARD SPEED, $\tau_{R1/2}$ PEAK ROLL STEER TORQUE, AND τ_{S1} PEAK STEER TORQUE WHEN THE RIDER UPPER BODY AND MOTORCYCLE ARE KEPT VERTICAL.

Test	**Handling Index**	**Good handling achieved when:**
Steady turning	Roll factor = τ/φ [7] Acceleration factor = $\tau/(V^2/R_c) \cong \tau/(g \tan\varphi)$ [7] Yaw factor = $\dot{\psi}/\delta$ [7]	Low values, small negative steer torque
U-turn	Koch index = $\tau_{peak}/(V\dot{\varphi}_{peak})$ [24]	Low values
Slalom	Roll transfer function = τ/φ [7]	Small phase
Lane Change	Lane Change Roll index = $\tau_{p-p}/(\dot{\varphi}_{p-p}V_{avg})$ [12] Rider control torque $\tau_{RC} = (\tau_{R2}/\tau - \tau_{R1}/\tau_{S1})\tau$ [29]	Low values $\partial\tau_{RC}/\partial V < 0$
Obstacle Avoidance	Time lag between τ and $\dot{\varphi}$ [7]	Small lag

cycles where the rider control torque decreases with increasing speed, that riders rate these as "lighter steering" than those where the rider control torque increases with increasing speed.

To research the level of detail necessary in motorcycle models to predict handling *Frendo et al.* [16] investigated the differences in handling indexes with three levels of model detail and compared to literature. They found that a non-linear tire model greatly influences the results. Interestingly the geometric parameter study on handling they carried out, found, trend wise, very little difference between the three different models, indicating that simple models can be used to predict relative handling improvements.

3.3 Handling Qualities For Racing

In racing the main goal is to complete a specified course in the shortest possible time. Rider comfort is only deemed of importance if it is a limiting factor for increasing speed and decreasing the lap time. Handling qualities for the racing 'role' are therefore linked to performance factors. Oddly enough, and despite there being a massive bicycle racing industry, handling quality research within the racing 'role' has only been performed on motorcycles. The only exception is the recent work by *Cangley et al.* [3] where they model the bicycle (including aerodynamic drag), track and rider, to determine the optimal bicycle for a specific time trial track. On the other hand a plethora of biomechanics, aerodynamics, physiology, frame and component stiffness and mass, and suspension dynamics research has been carried out over the years with respect to increasing cycling race performance levels [57, 60]. These investigations only focus on optimizing either the riders physical output level, or the material they were using and were never aimed at optimizing speeds for specific corners or the required rider control. Generally, but certainly for road bicycles this is the case, very little has changed over the last 110 years with respect to bicycle geometry other than the slope of the upper-tube and the result of adapting material and fabrication techniques. If this is because the design is already near to optimal with respect to handling for racing through the evolution process, or because there is no need for good handling qualities, we do not know. The rest of this section on handling qualities for racing will only focus on motorcycles.

The most active group in this area has been the group of Cossalter at Padua University who, for roughly the last 20 years, have been investigating motorcycle dynamics and control both theoretical and experimental. *Cossalter* [7] has clearly defined what he means when talking about 'directional stability', 'maneuverability' and 'handling' with respect to racing, they are:

Directional stability: *The ease with which a motorcycle naturally tends to maintain its equilibrium and follow a rectilinear path.* He continues by saying that this depends on the intrinsic vehicle characteristics; inertial properties of the motorcycle, forward speed, geometric properties of the steering head (which collectively determine the aligning effect of the trail), gyroscopic effects and tire properties.

Maneuverability: *an intrinsic vehicle performance measure relating its ability to do maneuvers to the time required to do the maneuver.* He can therefore quantify a vehicle's 'maneuverability' by finding the best performance (shortest time, longest distance covered in a specific time, the highest maneuver exit speed, etc.) that the vehicle can do on a specific maneuver and relate that to the performance of other vehicles on the same maneuver.

Handling: *is the ability of the vehicle to do complex maneuvers taking into consideration the driver's limits.* It is evaluated by comparing the control effort required for the different ve-

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hicles to perform their specific optimal maneuver, where less effort relates to a better handling vehicle. It does however, not include the riders mental workload.

To find an objective measure for maneuverability of motorcycles independently of the rider the theoretical ‘optimal maneuver method’ was developed by *Cossalter et al.* [9, 10]. It uses the concept of an ideal rider, that is, a rider that can perform any required (optimal) control, such that the vehicle can follow the best possible trajectory such that the highest performance is achieved on the maneuver. The optimal maneuver method thus is vehicle specific, determining an optimal control sequence for each vehicle for a specific maneuver, such that the maximum intrinsic vehicle performance can be compared to that of other vehicles on the same maneuver. Within the context of the ‘optimal maneuver method’ when the rider limitations (physical and physiological limits such as the maximum torque the rider is able to apply or maximum steering rate they are able to reach) are included as limitations in the ‘optimal control maneuver’ performance determination, then the best achieved performance quantifies the ‘handling’. As mental workload is not part of the criteria it seams that for racing purposes at least the best ‘handling’ bike for a specific circuit can be developed apriori.

A different approach to understanding maneuverability and handling is the concept of the instantaneous screw axis or Mozzi axis [11]. It has been used to distinguish different behaviors in transient maneuvers and identify the different phases of a maneuver [7, 11, 8]. They link the instantaneous screw axis with the concept of handling by noting that large movements of the screw axis trace correspond to demanding tasks. This once again makes handling an intrinsic characteristic of the machine and thus can be optimized to suit specific situations (accident avoidance or normal riding) or specific track layouts (racing).

Many researchers have tried to investigate handling and maneuverability using multi-body packages in combination with control (also for all vehicle roles not just racing). Certainly not all have been successful. We mention here just a few. *Beritta & Mitolo* [2] used performance indexes as a measure to investigate how design parameters affected the performance of a U-turn maneuver. *Giner et al.* [17] implemented rider motion as an inverted pendulum in a multi-body model of the motorcycle and rider based on motion capture data of real riders on a stationary motorcycle simulator. The pendulum control was based on the bike’s location in the corner and the equivalent motion capture measurements. The complete model however was not validated with real data. *Capitani et al.* [4] modeled a scooter with fixed rider in multi-body dynamics software and compared with measurements made with a real scooter for a lane change, J-turn, large and small radius 90° turn and a figure eight. The results did not compare well, which they suspected was a result of un-modeled rider motion, as the rider (inadvertently or unconsciously) used movement as part of the scooter maneuver control. This highlights a significant problem currently facing most multi-body model investigations, that it is unclear if the rider models used represent the real situations accurately enough despite all the (un-) modeled rider motions.

4 DISCUSSION AND CONCLUSIONS

Bicycle handling quality research has been driven by safety issues in particular accident avoidance, and no standard handling quality tests for bicycles have been developed. Consequently, there is no way to quantitatively compare the results of different bicycle handling experiments that have been carried out by the different authors. Contrary, motorcycle handling quality research has focussed mostly on determining quantifiable measures and repeatable testing procedures based around normal riding and racing situations. This has enabled authors to compare simulations and experiments often performed by different authors and often years apart. Therefore, for bicycle research it is also essential to develop a standardized set of tests and handling indexes, in a similar manner to those that exist for motorcycles, such that bicycle handling can be compared and quantified both experimentally and in simulations. Another advantage of such a set of handling tests is that the concept of handling qualities for normal riding can be determined, such that the designers, who now apply a time consuming trial and error method to developing new bicycle concepts, can determine a-priori what the handling qualities will be.

According to Cooper & Harper, handling qualities are a factor of the complete pilot-aircraft system and depend upon both the physical and mental workload of the pilot. Only measuring pilot’s output-rate feedback signal however, has been shown to correlate well with the handling qualities as perceived by the pilot. However, in single track vehicles, the rider has a large influence on the actual implementation of the maneuver, therefore comparing different riders output can be problematic. Furthermore, large differences have also been noted between the rider control for novice and experienced motorcycle riders. Finally, with the to-be developed bicycle handling indexes and standard tests in hand, the development of a set of design guidelines based on these indexes could help manufacturers to design bicycles that are better suited to a specific users such as novice, intermediate or expert riders.

REFERENCES

[1] Arnberg, P. W., and Tyden, T., 1974. Stability and maneuverability performance of different types of bicycles. Tech. Rep. 45 A, National Swedish Road and Traffic Research Institute.

[2] Beritta, R., and Mitolo, L., 2002. “Evaluation of motorcycle performance in u turn test using multibody code lms dads”. In ”High-Tech Cars And Engines”, Components,

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Materials, Technologies and Innovative Systems, Mostra-Convegno 30-31/5/2002.

[3] Cangley, P., Passfield, L., Carter, H., and Bailey, M., 2010. "Modelling mechanical enhancements in competitive cycling". In Proceedings, Bicycle and Motorcycle Dynamics 2010 Symposium on the Dynamics and Control of Single Track Vehicles, 20 - 22 October 2010, Delft, The Netherlands.

[4] Capitani, R., Masi, G., Meneghin, A., and Rosti, D., 2006. "Handling analysis of a two-wheeled vehicle using msc.adams/motorcycle". *Vehicle System Dynamics,* ***44***, p. 698707.

[5] Carvallo, E., 1899. *Théorie du mouvement du monocycle et de la bicyclette.* Gauthier-Villars, Paris, France. (Submitted in 1897 for the Prix Fourneyron, awarded shared second place in 1898.).

[6] Cooper, G. E., and Harper, R. P., 1969. The use of pilot rating in the evaluation of aircraft handling qualities. Tech. Rep. NASA TN D-5153, National Aeronautics and Space Administration (NASA), April.

[7] Cossalter, V., 2002. *Motorcycle Dynamics*. No. ISBN 0-9720514-0-6. Race Dynamics, Greendale, WI.

[8] Cossalter, V., Bellati, A., Doria, A., and Peretto, M., 2008. "Analysis of racing motorcycle performance with additional considerations for the mozzi axis". *Vehicle System Dynamics,* ***46***(Supplement), p. 815826.

[9] Cossalter, V., DaLio, M., Biral, F., and Fabbri, L., 1998. Evaluation of motorcycle maneuverability with the optimal maneuver method. Tech. Rep. 983022, SAE.

[10] Cossalter, V., DaLio, M., Lot, R., and Fabbri, L., 1999. "A general method for the evaluation of vehicle manoeuvrability with special emphasis on motorcycles". *Vehicle System Dynamics,* ***31***, pp. 113–135.

[11] Cossalter, V., and Doria, A., 2004. "Analysis of motorcycle slalom manoeuvres using the mozzi axis concept". *Vehicle Systeni Dynamics,* ***42***(3), pp. 175–194.

[12] Cossalter, V., and Sadauckas, J., 2006. "Elaboration and quantitative assessment of manoeuvrability for motorcycle lane change". *Vehicle System Dynamics,* ***44***(12), p. 903920.

[13] Dohring, E., 1953. "Uber die stabilitat und die lenkkrafte von einspurfahrzeugen.". PhD thesis, Braunschweig.

[14] Eaton, D., 1973. "Man-machine dynamics in the stabilization of single-track vehicles". PhD thesis, University of Michigan.

[15] Foale, T., 2006. *Motorcycle Handling and Chasis Design*. Mediaprint.

[16] Frendo, F., Sisi, A., Guiggiani, M., and DiPiazza, S., 2006. "Analysis of motorcycle models for the evaluation of the handling performances". *Vehicle System Dynamics,* ***44***(Supplement), p. 2006.

[17] Giner, D. M., Brenna, C., Symeonidis, I., and Kavadarlic, G., 2008. "Mymosa towards the simulation of realistic motorcycle manoeuvres by coupling multibody and control techniques". In Proceedings of IMECE2008 2008 ASME International Mechanical Engineering Congress and Exposition November 2-6, 2008, Boston, Massachusetts, USA, no. IMECE2008-67297, p. 13.

[18] Godthelp, J. ., and Buist, M., 1975. Stability and manoeuvrability characteristics of single track vehicles. Tech. Rep. IZF 1975 C-2, TNO - IZF.

[19] Godthelp, J., and Wouters, P., 1978. "Koers houden door fietsers en bromfietsers". *Verkeerskunde*(11), November, pp. 537 – 543.

[20] Herfkens, B. D., 1949. De stabiliteit van het rijwiel. Tech. rep., Instituut voor Rijwielontwikkeling.

[21] Herlihy, D. V., 2004. *Bicycle: The History*. New Haven and London: Yale University Press, 2004. ISBN: 0300120478, 9780300120479.

[22] Hess, R., 1977. "Prediction of pilot opinion ratings using an optimal pilot model". *Human Factors: The Journal of the Human Factors and Ergonomics Society,* ***19***(5), pp. 459–475.

[23] Jones, D. E. H., 1970. "The stability of the bicycle.". *Physics Today,* ***23***(4), pp. 34–40. (reprinted in September 2006).

[24] Koch, J., 1978. "Experimentelle und analytische untersuchungen des motorrad-fahrer systems.". PhD thesis, Berlin.

[25] Kooijman, J. D. G., Meijaard, J. P., Papadopoulos, J. M., Ruina, A., and Schwab, A. L., 2011. "A bicycle can be self-stable without gyroscopic or caster effects". *Science,* ***332***(6027), pp. 339–342.

[26] Kooijman, J. D. G., Meijaard, J. P., Papadopoulos, J. M., Ruina, A., and Schwab, A. L., 2011. "A bicycle can be self-stable without gyroscopic or caster effects". *Science,* ***332***(6027), pp. 339–342. Supporting Online Material Text Section 1–11.

[27] Kooijman, J. D. G., and Schwab, A. L., 2009. "Experimental validation of the lateral dynamics of a bicycle on a treadmill". In Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2009 August 30-September 2, 2009, San Diego, USA.

[28] Kooijman, J. D. G., Schwab, A. L., and Meijaard, J. P., 2008. "Experimental validation of a model of an uncontrolled bicycle". *Multibody System Dynamics,* ***19***, pp. 115–132.

[29] Kuroiwa, O., Baba, M., and Nakata, N., 1995. Study of motorcycle handling characteristics and rider feeling during lane change. Tech. Rep. 950200, SAE.

[30] McRuer, D., and Jex, H., 1967. "A review of quasi-linear pilot models". *Human Factors in Electronics, IEEE Transactions on,* ***HFE-8***(3), Sept., pp. 231–249.

Copyright © 2011 by ASME

[31] Means, J., 1896. "Wheeling and flying". *The Aeronautical Annual 1896,* ***2***, pp. 23–25.
[32] Meijaard, J., Papadopoulos, J. M., Ruina, A., and Schwab, A., 2007. "Linearized dynamics equations for the balance and steer of a bicycle: a benchmark and review". *Proceedings of the Royal Society A,* ***463***, p. 19551982.
[33] Meijaard, J., Papadopoulos, J. M., Ruina, A., and Schwab, A., 2011. "History of thoughts about bicycle self-stability". *eCommons@Cornell*.
[34] Moore, J. K., Hubbard, M., Schwab, A. L., and Kooijman, J. D. G., 2010. "Accurate measurement of bicycle parameters". In Proceedings, Bicycle and Motorcycle Dynamics 2010 Symposium on the Dynamics and Control of Single Track Vehicles, 2022 October 2010, Delft, The Netherlands.
[35] Mortimer, R. G., Domas, P. A., and Dewar, R. E., 1973. The relationship of bicycle maneuverability to handlebar configuration. Tech. Rep. UM-HSRI-HF-TM-73-5, Highway Safety Research Institute, University of Michigan,, Univeristy of Michigan, Huron Parkway & Baxter Road, Ann Arbor, Michigan 48105, June.
[36] Patterson, W. B., 2004. *Lords of the Chainring*. Santa Maria.
[37] Popov, A. A., Rowell, S., and Meijaard, J. P., 2010. "A review on motorcycle and rider modelling for steering control". *Vehicle System Dynamics,* ***48***, pp. 775–792.
[38] Prem, H., and Good, M. C., 1984. Motorcycle rider skills assessment. Tech. rep., University of Melbourn.
[39] Rankine, W. J. M., 1869. "On the dynamical principles of the motion of velocipedes.". *The Engineer,* ***28***, pp. 79,129,153,175 and 29:2 (1870).
[40] Rice, R. S., 1975. "Accident avoidance capabilities of motorcycles". In Procedings International Motorcycle Safety Conference, December 16-17 1975, U.S. Department of Transportation, National Highway Traffic Safety Administration, Washington D.C., pp. 121–134.
[41] Rice, R. S., 1978. Rider skill influences on motorcycle maneuvering. Tech. Rep. 780312, SAE. SP-428.
[42] Rice, R. S., Davis, J. A., and Kunkel, D. T., 1975. Accident-avoidance capabilities of motorcycles. Tech. Rep. ZN- 5571-V-1 and ZN- 5571-V-2, Calspan Corporation, Calspan Corporation 4455 Genesee Street Buffalo, New York 14221, June. V-1 = Aeport, V-2 = Appendices.
[43] Rice, R. S., and Kunkel, D., 1976. Accident avoidance capabilities of motorcycles - lane change maneuver simulation and full-scale tests. Tech. Rep. ZN-5899-V-1, Calspan Corporation.
[44] Rice, R. S., and Roland, R. D., 1970. An evaluation of the perfomance and handling qualities of bicycles. Tech. rep., Cornell Aero. Lab. Rept. VJ-2888-K, April.
[45] Roland, R., and Lynch, J., 1972. Bicycle dynamics tire characteristics and rider modeling. Tech. Rep. YA-3063-K-2, Cornell Aeronautical Labaratory, Inc. Buffalo, NY,, March.
[46] Roland, R., and Massing, D. E., 1971. A digital computer simulation of bicycle dynamics. Tech. Rep. YA-3063-K-1, Cornell Aeronautical Laboratory, Inc. Buffalo, NY., June.
[47] Sharp, R. S., 1971. "The stability and control of motorcycles". *Journal of Mechanical Engineering Science,* ***13***(5), pp. 316–329.
[48] Sharp, R. S., 1978. "A review of motorcycle steering behavior and straight line stability characteristics". In Motorcycle Dynamics and Rider Control, SAE Congress Detroit Michigan Feb 27 - Mar 03 1978, no. 780303 in SP-428, SAE.
[49] Sharp, R. S., 2008. "On the stability and control of the bicycle". *Applied Mechanics Reviews,* ***61***, November, 24 pp.
[50] Stevens, D., 2009. "The stability and handling characteristics of bicycles". Bachelor of science thesis, The university of new south wales, school of mechanical and manufacturing engineering.
[51] Tak, T.-O. T., Won, J.-S., and Baek, G.-Y., 2010. "Design sensitivity analysis of bicycle stability and experimental validation". In Proceedings, Bicycle and Motorcycle Dynamics 2010 Symposium on the Dynamics and Control of Single Track Vehicles, 20 - 22 October 2010, Delft, The Netherlands.
[52] Watanabe, Y., and Yoshida, K., 1973. *Motorcycle handling performance for obstacle avoidance*. Dept. of Transportation.
[53] Weir, D. H., 1972. "Motorcycle handling dynamics and rider control and the effect of design configuration on response and performance". PhD thesis, University of California, LA.
[54] Whipple, F. J. W., 1899. "The stability of the motion of a bicycle". *Quarterly Journal of Pure and Applied Mathematics,* ***30***, pp. 312–348.
[55] Wierda, M., and Roos, E., 1988. *Gangbare kinderfietsen op comfort, manoeuvreerbaarheid en remweg vergeleken*. Haren: Verkeerskundig Studiecentrum, Rijksuniversiteit Groningen.
[56] Wierda, M., and Wolf, J., 1989. *Drie typen kinderfietsen op manoeuvreerbaarheid en remweg vergeleken*. Haren.
[57] Wilson, D. G., 2004. *Bicycling Science*, 3rd ed. The MIT Press. (with contributions by J. M. Papadopoulos).
[58] Zellner, J. W., and Weir, D. H., 1978. Development of handling test procedures for motorcycles. Tech. Rep. 780313, SAE.
[59] Zellner, J. W., and Weir, D. H., 1979. Moped directional dynamics and handling qualities. Tech. Rep. 790260, SAE.
[60] Zinn, L., 1998. *Mountain Bike Performance Handbook*. MBI.

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