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Dipl.-Ing. Kai Gerd Schröter,
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Brake Steer Torque Optimized Corner Braking of Motorcycles

Bremslenkmomentoptimierte Kurvenbremsung von Motorrädern

FZD FAHRZEUGTECHNIK TU DARMSTADT

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Am Fachbereich Maschinenbau an der
Technischen Universität Darmstadt
zur Erlangung des Grades eines
Doktor-Ingenieurs (Dr.-Ing.)
genehmigte

Dissertation

vorgelegt von

Dipl.-Ing. Kai Gerd Schröter
aus Gelnhausen

Berichterstatter:	Prof. Dr. rer. nat. Hermann Winner
Mitberichterstatter:	Prof. Dr.-Ing. Markus Lienkamp
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This thesis deals with the Brake Steer Torque (BST) induced stand-up tendency of Powered Two Wheelers (PTW) and measures to lower the associated risk for running wide on curve accidents with sudden, unforeseen braking. Focus is set on the BST Avoidance Mechanism (BSTAM), a chassis design that eliminates the BST through lateral inclination of the kinematic steering axis. A simple mathematical model is used to identify its main influences on the driving behavior and derive an optimized system layout. Its theoretical potential is evaluated against the standard chassis using different cornering adaptive brake force distributions and riding styles. For the first time ever, a motorcycle with state-of-the-art brake system (Honda CBR 600 RR, C-ABS) is equipped with a BSTAM and tested in corner braking experiments. Compared to the baseline, it is significantly reducing BST related disturbances and improving directional control. The gained insights can be stepping stones to enhance PTW safety by enabling future assistance systems with autonomous corner braking.

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Finally, I praise God whom I cannot thank enough for revealing a glimpse at the beauty of creation concealed in motorcycle dynamics and for making this daring adventure possible for me.

Dear reader, may He bless you richly and always keep you safe on the road.

And now: Enjoy reading!

Kai Schröter Mühltal, in December 2014

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Contents

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List of Abbreviations

Abbreviation	Description
ABS	Antilock Brake System
ACT.	Actuator (i.e. BSTAM actuator)
AEB	Autonomous Emergency Braking
ARAS	Advanced Rider Assistance System (cf. ADAS for passenger cars, with D for driver)
BFD (CA-BFD)	(Cornering Adaptive) Brake Force Distribution
BPM	Brake Pitch Moment
BST	Brake Steer Torque
(//)BSTAM	Brake Steer Torque Avoidance Mechanism (with parallel steering axis offset)
OPT BSTAM	BSTAM with optimized instantaneous center of steering axis inclination
BYM	Brake Yaw Moment
CBS	Combined Brake System
C-ABS	Combined Antilock Brake System (Brake-by-Wire)
CoG	Center of Gravity
CoSy	Coordinate System
CTR	A chassis setup with centered steering axis (either standard, or passive BSTAM)
DoF	Degree of Freedom
DS	Displacement Sensitivity
EEF	Excentricity Enlargement Factor
EXP	Experiments
FZD	Institute of Automotive Engineering Darmstadt
GPS	Global Positioning System
HESD	Honda Electronic Steering Damper
IMU	Inertial Measurement Unit
KPI	King-Pin Inclination (angle between (projected) steering axis and symmetry plane)
MBS	Multi Body Simulation
MSC	Motorcycle Stability Control
PBA	Predictive Brake Assist
PMC	Prototype Motorcycle
PTW	Powered Two (and Three) Wheeler
RLP	Rear Wheel Lift-Off Protection
RMS	Root Mean Square
STA	Standard setup / Standard chassis with centered steering axis
STD	Steering Torque Demand
TCS	Traction Control System
TU Darmstadt	Technische Universität Darmstadt
VRU	Vulnerable Road User

Abbreviations that occur only once are explained in context and not contained in this list.

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List of Symbols and Indices

Symbol	Unit	Description
a_x	m/s² | g	longitudinal acceleration, mainly: deceleration
a_y	m/s² | g	lateral acceleration
bd	m	bearing distance (perpendicular distance between the kinematic center points of the steering bearings measured along the fork legs / conventional steering axis, in z'_{st}-direction)
c_w	-	aerodynamic drag coefficient
c_l	-	aerodynamic lift coefficient
c_p	-	aerodynamic pitch moment coefficient
c_{roll}	-	rolling resistance coefficient
d	m	displacement, offset, diameter
e	m	BSTAM excentricity
ecr	% | -	effective compensation ratio
f	Hz	frequency
fl	m	fork length (perpendicular distance between the kinematic center of the lower steering bearing and front wheel hub, measured along the fork legs)
fo	m	fork (yoke) offset (perpendicular distance between standard steering axis and front wheel axle, measured along x'_{st}-axis)
g	m/s², N/kg	gravitational acceleration, gravity constant
g_1, g_2	various	slope and axis intercept parameters of linear regression of data correlations
gcr	% | -	geometric compensation ratio
h	m	height
i	A	electrical current
l	m	length, geometric chassis parameter, lever arm, wheelbase
$l_{x,y,z}$	m	lever arms of front tire longitudinal, lateral, and vertical contact forces towards the steering axis
ℓ_{yz}	-	lever ratio (of lateral and normal force levers)
$\mathcal{L}$, $\mathcal{L}_x$, $\mathcal{L}_{yz}$	-	relative lever ratio (ratio of lever ratios of different setups)
m	kg	mass
n	m	trail
nt	m	normal trail
p	bar | -	pressure, brake pressure, tire inflation pressure | probability of a correlation
r	m	tire rolling radius in center position ($\lambda = 0$)
r_c	m	tire contour (or: cross-section) radius
r_r	m	roll angle dependent tire rolling radius
s	% | -	tire (brake) slip
sr	m	scrub radius (lateral lever arm from tire contact point towards steering axis)
t	s	time
tcr	% | -	target compensation ratio
$trigger$	-	trigger signal from the brake light switch
v	m/s | km/h	velocity, speed (vehicle or front wheel circumferential speed)

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Symbol	Unit	Description
x, y	various	abscissa and ordinate parameters for correlation analysis and linear regression
A	m²	Area (i.e. the projected frontal area of the vehicle with rider and equipment)
DS	mm/°	Displacement Sensitivity
EEF	-	Excentricity Enlargement Factor
F	N	force
I	kgm²	mass moment of inertia
L	-	length of a straight road | length of whiskers in box-plots (rel. to data spread)
M	Nm	moment
Q	-	quartile (eg. Q_1 and Q_3 for the 25th and 75th percentile of data)
R	m | -	curve radius | correlation coefficient
T	Nm	torque, steering torque, braking torque, driving torque
α	°	(tire) sideslip angle | curve opening angle
β	°	vehicle sideslip angle
χ	°	rider lean angle (relative to motorcycle frame)
δ	°	steering angle
ε	°	BSTAM excenter actuation angle
γ	°	steering axis inclination angle from vertical (x-z-plane)
λ	°	roll angle
μ	-	(available or utilized) friction potential
ν	°	pitch angle
σ	° | -	king-pin inclination angle of steering axis relative to vehicle symmetry plane (x'-z'-plane) | standard deviation of data (separately indicated)
ρ	kg/m³	air density
τ	°	steering head (or caster) angle
ω	°/s | rad/s	angular velocity
ψ	°	yaw angle
Δ	-	Difference
a, c, e	N	Substitute coefficients
b, d, f	kg	Substitute coefficients

Some of the utilized symbols are also used as indices and are therefore not necessarily repeated in the list of indices.

Index	Description
0	initial condition, at the beginning of an experiment ($t = 0$), or upright vehicle position ($\lambda = 0$)
Ackermann	concerning the Ackermann condition (i.e. the Ackermann steering angle)
(//)BSTAM	related to a (//) BSTAM
BPM	Brake Pitch Moment
BYM	Brake Yaw Moment
STA, sta	(related to the) standard setup with centered steering axis
ac	related to the aerodynamic center
aero	concerning an aerodynamic influence
available	available portion (e.g. of the friction potential μ)
brk, brake	related to brakes or braking
cg, CoG	(related to the) center of gravity

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Index	**Description**
demand	demand
drag	concerning aerodynamic drag
drive	related to driving forces or torques
dyn	dynamic
eff	effective
end	related to the end of an experiment
friction	concerning friction / friction limits
ft	front
gyro	related to a gyroscope
i	general index parameter
inertia	concerning the "Inertia Effect"
is	concerning the "is" value of a measured variable at a certain point in time
lift	concerning aerodynamic lift
limit	concerning a limiting value
lower	lower threshold value
max	maximal
mean	mean, averaged value
opt	optimal, optimized, related to (the definition of) an optimized (OPT) BSTAM
partial	partial
pitch	concerning the pitch degree of freedom
precession	concerning the precession of a gyroscope
red	reduced
ref	reference
rel	relative
rider	(related to the) rider
rlp	concerning rear wheel lift-off conditions
roll	concerning the roll degree of freedom | concerning the rolling resistance of tires
rr	rear
spin	concerning the spinning of a gyroscope
st	related to steering / the steering system
target	concerning a target value
th	theoretical, physically active (referring to the roll angle)
tir, tire	related to tires (typically the front tire)
tot	total
upper	upper threshold value
used	used or utilized portion (e.g. of the friction potential μ)
whl, wheel	related to a wheel (typically the front wheel)
x, y, z	in/from x-direction (longitudinal), y-direction (lateral), z-direction (vertical)
yaw	concerning the yaw degree of freedom

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Summary

Motorcyclists account for an alarmingly high share among traffic fatalities and severely injured. Especially in unforeseen or hazardous corner braking situations, riders often show a limited capability to balance their brake action and compensation of the Brake Steer Torque (BST) instantaneously. In many cases, the subsequent stand-up tendency of the vehicle can further confuse the rider which might run off track or into oncoming traffic. Since the BST mainly arises as a product of the front brake force with the roll angle dependent tire scrub radius as lateral lever arm, Weidele proposed the so-called BST Avoidance Mechanism (BSTAM), inhibiting BST generation by lateral inclination of the steering axis. The system was however never analyzed or practically tested beyond the demonstration of mechanical feasibility in the early 1990s. Therefore, research objectives lie in the evaluation of a BSTAM's performance and benefit for the rider before the background of the past decades' tremendous improvements in state-of-the-art technology, as well as to find criteria for a favorable system design.

As starting point, influence factors on the BST chain of effects are identified and used as classification scheme for countermeasures, ranging from possibilities of rider training or road design to technical measures on the vehicle. Besides BSTAM, a counter steering actuator, Cornering Adaptive Brake Force Distribution (CA-BFD), semi-active steering dampers, and multi-lever steering are identified as promising.

Focusing on the transmission ratios of front tire contact forces towards the steering axis as the main contributes affected by BSTAM, a simple mathematical model is used to analyze the steering torque demand (STD) of a generic BSTAM against that of the baseline chassis. The balance between normal and lateral force is found to be crucial for a "neutral" steering. Compensation of the tire scrub radius through BSTAM not only eliminates the disturbing influence of the brake force, but also diminishes helpful aligning steering torque components generated by the normal and lateral force, leading to an undesired increase in STD. Kinematic optimization resolves this trade-off for steering axis inclination angles in the order of 10° with an optimal instantaneous center of steering axis rotation located at the intersection of the original steering axis with the vertical connection from tire contact point to wheel hub in upright position. Small steering disturbances arising from the deceleration of wheel spin inertia and inertial forces on the steering system can be accounted for through limitation of front brake pressure gradients and by keeping the instantaneous center of steering axis inclination close to the steering system's center of gravity. An analysis of BSTAM concepts with parallel steering axis adjustment yields acceptable steering balance only for unusually large caster angles and fork offsets (around 50° and 140 mm). However, these setups suffer consid-

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erable disturbances through longitudinal accelerations on the steering system (in the order of 10 Nm) and were not further pursued. Also an exemplary analysis of multi-lever steering (i.e. a four-bar linkage) showed no benefits regarding the BST.

Using methods of product design, key aspects of incorporating an optimized BSTAM into a vehicle are investigated and four classes of alternative actuation concepts proposed, that may be favorably incorporated basing on a king-pin or hub-center steering.

For the first time ever, a Honda CBR 600 RR super-sport motorcycle with Combined-ABS and a conventional telescopic fork is equipped with a BSTAM according to Weidele's original design with double excentric adjustment of the upper steering head bearing and tested against the baseline in comparative riding tests.

Correlation analysis of all conducted tests confirms the BST chain of effects, interconnecting disturbances in steering torque, steering angle, roll angle, and also rider lean angle. Moreover, it shows a strong dependency of the disturbance values on the initial brake pressure increase rate and mean deceleration for centered steering axis, while BSTAM eliminates this correlation to a great extend.

In line with predictions from model calculations, riding tests with the baseline chassis confirm a positive influence of "lean in" riding style. For maximal braking, the "stand-up" of the vehicle matches well with the required reductions in roll angle towards lower speeds, provided the maneuver is done intentionally on the test track.

Comparison of baseline and BSTAM in partial front braking maneuvers fully confirms the behavior expected from model calculations. On one hand, handling is compromised due to increases in caster angle and trail (handling index 3.0-3.3 vs. 4.9 $^{\mathrm{Ncm}}/_{(\mathrm{m}^{\circ}/\mathrm{s}^{2})}$) and the stationary STD is significantly increased (5.3 vs. 20.9 Nm). On the other, significant reductions are obtained in steering torque deviations upon brake kick-in (21.2 vs. 13.4 Nm), followed by significant improvements in all other disturbance values. Moreover, BSTAM eases directional controllability for braking on narrowing radius turns.

Even though BSTAM proves already effective in the prototype setup and further improvements are expected from the proposed optimizations, especially concerning stationary STD, stability and handling characteristics require further investigations. Moreover, a simulation study reveals, that Cornering Adaptive Brake Force Distribution already reduces the expected disturbance values in partial braking to such low absolute levels, that this measure alone bears the potential to address a great deal of BST relevant situations in real traffic and might further be complimented by advanced semi-active steering damper control. However, before the background of current discussions on the implementation of predictive brake assist or even autonomous emergency braking into powered two wheelers, effective BST countermeasures are a necessary prerequisite. In these regards, a model based counter steering torque actuator as an add-on to the well understood conventional chassis is regarded as to be superior compared to BSTAM.

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I dedicate this thesis to

GOD, the creator of heaven and earth,

JESUS CHRIST, my Lord and Savior, through whom all things are made, and to the

HOLY SPIRIT, eternal inspiration for every good work.

SOLI DEO GLORIA.

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