

Advances in Motorcycle Dynamics: Emerging Trends and Methodologies in Vehicle Simulation and Safety Optimisation

Iatrakis Gideon Ilias

^aDepartment, University, City, Country; ^bDepartment, University, City, Country

University of Wales Trinity Saint David

2011922@student.uwtsd.ac.uk

Msc Motorcycle Engineering

No Conflict of Interest Statement:

The author declares that there are no conflicts of interest regarding the publication of this paper. This research was conducted independently and impartially, with no financial or personal relationships that could have influenced the work presented in this manuscript.

Advances in Motorcycle Dynamics: Emerging Trends and methodologies in Vehicle Simulation and Safety Optimisation

This paper presents a comprehensive review of recent advancements in Motorcycle Dynamics, a field that has experienced significant growth in both theoretical and applied research. The focus is on how current studies have enhanced the authenticity, accuracy, and applicability of simulation models in motorcycle dynamics, particularly in racing contexts. Key areas of advancement include the development of quasi-steady-state models for lap time simulation, optimal control methods for g-g diagram computation, and innovative approaches to tire wear modelling. The review also delves into the dynamics of driveline stability, the intricacies of engine braking, and the emerging importance of data-driven methodologies in understanding rider dynamics. Moreover, the paper examines the evolving landscape of motorcycle safety technologies, discussing recent explorations into emergency steering assistance, autonomous emergency braking systems, and the analysis of rider response in critical scenarios. The integration of these technologies into dynamic models is highlighted, underscoring their potential to enhance rider safety. Furthermore, the study explores the predictive modelling of control loss during emergency manoeuvres and the effects of simulator configurations on steering and gaze behaviour, providing insights into rider behaviour and training. The culmination of these studies presents a multi-faceted view of Motorcycle Dynamics, illustrating its vital role in advancing vehicle performance and safety. The paper concludes by identifying future research directions, emphasizing the growing importance of this field in shaping the next generation of motorcycle technology and rider safety mechanisms.

Keywords: Vehicle Dynamics; Motorcycle; Race performance analysis, Simulation, Motorcycle Safety

INTRODUCTION

The field of Motorcycle Dynamics has witnessed considerable advancements in recent years, compared to other vesicle dynamics disciplines. This study aims to review these evolvments, highlighting significant progress in simulation techniques and model realism. The main points of view are development in relationship to the optimization of motorcycle performance, particularly in the racing context. Various methodologies have been studied, to create a properly balanced and comprehensive overview of some of the progress made in Motorcycle Dynamics, with its main factor being the increasing accuracy and applicability of these advanced models.

1: Quasi-Steady-State Minimum Lap Time Simulation of race motorcycles using experimental data

Biniewicz, J., Pyrz, M. [1] have proposed a quasi-steady-state (QSS) approach for motorcycle race simulations using experimental data to create accurate g-g diagrams. By applying variable acceleration limits at different velocities and incorporating jerk constraints from real-world data, the method improves the realism of trajectory simulations. A hybrid g-g diagram is proposed using both experimental and theoretical acceleration limits. This ensures that the model's predicted manoeuvres, particularly in braking and turning, are feasible for riders, thus avoiding unrealistic 'bang-bang' manoeuvres. The approach enhances the accuracy of racing performance simulations, providing a more reliable tool for drivers to optimize their on-track strategies. While the method depends on the availability and quality of experimental data, it represents a significant step forward in creating more realistic and applicable simulation methods for motorcycle racing dynamics.

2: An optimal control approach to the computation of g-g diagrams.

Building on the need for smoother g-g diagrams, Massaro M. et al.[2] Have proposed an optimal control (OCP) method for vehicle simulation, enhancing the computation of g-g diagrams by maximizing their area. This approach ensures smooth transitions between vehicle states, particularly in steering and slip, and is achieved by incorporating a regularization term [3] in the computation methods. This term effectively avoids abrupt 'bang-bang' inputs, common in traditional simulation models. Applied to a double-track car model with nonlinear tires, the OCP method demonstrates its ability to control the rate of change in vehicle states across the g-g envelope, facilitating both regular and powerslide cornering solutions.

3: g-g-g Extension - A three-dimensional free-trajectory quasi-steady-state optimal-control method for minimum-lap-time of race vehicles

For enhanced simulation accuracy, a method for expanding two-dimensional g-g diagrams into a three-dimensional format (g-g-g) has been proposed, especially useful when inertial moment platform data is unavailable [4]. This approach calculates the vertical component of the g-g-g map using longitudinal and vertical accelerations, coupled with motorcycle motion equations[5]. The g-g-g maps incorporate limits on acceleration and deceleration due to factors like friction, engine power, wheelies, stoppies, and optimal brake ratios. Each point in the optimal control problem (OCP) solution corresponds to a point on the g-g-g diagram, representing quasi-steady-state vehicle conditions. The OCP can be numerically solved using direct or indirect methods [5], [6], with jerk control speeding up the solution despite increasing equation complexity. This method is significantly faster than full-dynamic models, reducing computation time by a factor of 10.

Comparing fixed trajectory OCP to free trajectory, differences in lap times are minor (0.2s on Mugello and 0.4s on Catalunya), suggesting the fixed trajectory method as a viable option when trajectory optimization isn't critical. This three-dimensional approach, applicable to both motorcycles and cars, considers the effects of speed, banking, and slope on the g-g-g diagrams.

4: Three-dimensional fixed-trajectory approaches to the minimum-lap time of road vehicles

S. Lovato et al. [7] have proposed advanced optimal control methods for minimal lap time calculation in road vehicles, utilising quasi-steady-state (QSS) models on three-dimensional racing lines. This approach, which marks a significant progression from traditional two-dimensional models, employs two methodologies: an adaptation of the apex-finding method to three dimensions (considering elevation, slope, and banking) and an alternative based on simple optimal control problems. Both utilize g-g-g diagrams, extending the conventional g-g diagrams to a three-dimensional context.

A crucial distinction between these 3D and 2D models lies in their handling of speed minima at corner apexes. In 2D simulations, minimal speed typically occurs after the apex due to necessary small negative longitudinal acceleration for maximal lateral acceleration. However, 3D models, accounting for elevation changes, show that longitudinal acceleration at the apex can vary, being negative on flat terrain or positive when descending, influencing the positioning of speed minima relative to the apex. This 3D modelling approach results in a significant 3-4 second difference in lap times compared to 2D simulations, around Mugello, highlighting the importance of incorporating dimensional accuracy in vehicle dynamics simulations. Despite the apex-finding method being slower in computation than the fixed trajectory OCP, both

methods offer a substantial reduction in computation time compared to dynamic models without predefined trajectories.

5: Tyre wear modelling approach for vehicle dynamics simulation and control oriented analyses with application to motorcycles

Radrizzani et al. [8] proposes a tyre wear modelling approach, addressing a gap in existing literature, by considering how vehicle dynamics influence tyre wear and vice versa, particularly in how wear affects tire force exertion. . This approach improves accuracy by reflecting tire and vehicle behaviour over time, useful for strategic development in racing. A simple tire brush model is employed for accurately capturing local tire-road frictional interactions, supplemented by a mass loss model to quantify tire wear effects on dynamics. Additionally, Pacejka's Magic Formula, an empirical parametric model, is utilized to comprehensively describe tire forces' static and dynamic properties, considering factors like temperature, pressure, and stress, as well as wear phenomena such as graining and blistering [9]–[11].

6: Driveline Stability in Racing Motorcycles: Analysis of a Three Degrees of Freedom Minimal Mode

Schramm A Et All. [12], provided an enhancement in motorcycle simulation methods by analysing stability under braking, focusing on the influence of roll angle and tyre lateral force dynamics. By incorporating roll angle as a third degree of freedom, the model predicts rear system instabilities in various manoeuvres, utilizing Pacejka's Magic Formula for tire modelling [9]. Findings indicate that instabilities, particularly in the chatter mode, found to be with a frequency around 19Hz [13], are influenced by the interplay of tire force gradient parameters and the phase relationship between swingarm angle and wheel speed oscillations. Key stability factors include the natural frequencies of the driveline, tire vertical stiffness, chain stiffness, and rear wheel properties.

Adjusting the chain-to-swingarm angle also emerges as a stabilization strategy, underscoring the model's contribution to more realistic motorcycle behaviour simulations.

7: Motorcycle Engine braking deceleration analysis

Cieпка P. Et Al. [14] have executed a series of experimental tests, the study assessed engine braking deceleration across 26 motorcycles of various ages, types and sizes, addressing a gap in vehicle dynamics literature, where engine braking is not often considered. The research found no significant differences in engine braking magnitude across motorcycle types or engine sizes. A noted limitation is the exclusion of aerodynamic resistance. The study offers polynomial equations relating deceleration to velocity for each gear, serving as a robust foundation for further modelling, and provides critical data for theoretical analysis and practical application in accident reconstruction scenarios.

8: Data driven methodology for the investigation of riding dynamics: a motorcycle case study

Bartolozzi M. Et Al., [15] have aimed to enhance the understanding of rider interactions with Powered-Two-Wheelers (PTWs), especially in bend manoeuvres where accident risks are high. Utilizing an unsupervised, data-driven methodology, it segments and clusters extensive riding data to objectively analyse motorcycle lateral dynamics. The method employs unsupervised learning algorithms to categorize riding behaviours into distinct clusters without predefined labels. Key input signals like roll angle, rate, and acceleration are used to differentiate cornering phases, enabling detailed analysis of various riding conditions. Results from this segmentation and clustering reveal distinct behavioural patterns and dynamics in various cornering manoeuvres, carried out by a professional, offering insights not readily discernible from raw data. This approach

significantly advances the understanding of motorcycle dynamics and rider behaviour, with implications for rider training, safety device development, and accident reconstruction. By providing nuanced insights into rider-motorcycle interactions, particularly in cornering, the study contributes to the development of more accurate and realistic motorcycle dynamics models, enhancing simulation accuracy and informing parameter variability analysis for dynamic modelling.

9: Motorcycle emergency steering assistance: evaluation and rider experience

Bartolozzi M. Et Al. [16] evaluated emergency steering assistance systems for motorcycles, such as Motorcycle Curve Assist (MCA), Motorcycle Stabilisation (MS), and Motorcycle Autonomous Emergency Steering (MAES). Using crash configuration analysis, the study found MAES to be highly effective in aiding lateral avoidance manoeuvres. This research demonstrates the potential of dynamic vehicle models in developing and fine-tuning such safety systems, with rider feedback confirming the feasibility of external steering interventions without compromising control.

10: The development of a test method for motorcycle autonomous emergency braking systems

Merkel N. [17] reviewed the development of Motorcycle Autonomous Emergency Braking (MAEB) systems, emphasizing their effectiveness in optimizing safe decelerations. It revealed that different braking strategies, such as block and ramp reactions, influence rider control and response during autonomous braking. This insight is crucial for constructing accurate g-g diagrams in simulations, enhancing the realism of various riding scenarios.

11: Analysis of the rider's body movement during the intervention of the Autonomous Emergency Braking system for Motorcycles (MAEB)

Cassese G. Et Al [18] analysed rider body movement during MAEB interventions in straight-line riding conditions. Utilizing video analysis and sensor data, the study identified different rider behaviours in response to automatic braking, confirming MAEB's safety application in real conditions. This methodology provides a foundational understanding of rider reactions to sudden braking events.

12: Loss of control prediction for motorcycles during emergency braking manoeuvres using a supervised learning algorithm.

Huertas P. Et al. [19] presented predictive models using supervised learning algorithms to classify loss of control events during emergency braking manoeuvres. The study, involving 165 braking trials with varying rider skill levels, found that parameters like yaw rate and front-wheel lock duration are key predictors of control loss. This research supports the development of active safety systems and targeted rider training programs, improving emergency response capabilities.

13: Dynamic modelling of an unmanned motorcycle and combined balance control with both steering and double CMG's

Zheng X. et al. [20] explored dynamic modelling of unmanned motorcycles equipped with steering and double Control Moment Gyroscopes (CMGs). This research advances our understanding of vehicle dynamics and contributes to the development of control strategies and component assessment without human risk. The study demonstrates the advantages of combined balance control, particularly in low and high forward velocity scenarios.

14: Effects of motorcycle simulator configurations on steering control and gaze behaviour in bends

Lobjois R. et al. [21] examined the effects of motorcycle simulator configurations on steering control and gaze behaviour. The study highlighted the realism of reverse steering in simulations, despite challenges in accurately modelling internal vehicle dynamics. This finding underscores the importance of precisely representing countersteering measures for realistic simulation methods.

15: Evaluating rider response steering to an unexpected collision hazard using a motorcycle simulator

Nugent M. et Al. [22] investigated rider response to unexpected collision hazards using a motorcycle simulator, focusing on time-to-crash (TTC) durations. The study's results, showing variability in rider responses based on TTC, provide valuable insights for designing effective rider assistance systems and for behavioural modelling in traffic scenarios.

CONCLUSION

This study aimed to review the remarkable advancements in Motorcycle Dynamics to get a deeper understanding of this rapidly evolving field. Significant progress in simulation accuracy, tire wear modelling, vehicle stability, and rider safety were the main points of this study. These advancements, collectively contribute to a broader understanding of motorcycle behaviour, enhancing both performance optimization and most importantly rider safety. Further research should continue to focus on refining these models, particularly on the topic of real-world applicability and rider interaction. As Motorcycle Dynamics continue to evolve, its implications for racing strategy, vehicle design, and safety technology become increasingly important, which will result in promising outcomes in this field.

- [1] J. Biniewicz and M. Pyrz, "A quasi-steady-state minimum lap time simulation of race motorcycles using experimental data," *Vehicle System Dynamics*, 2023, doi: 10.1080/00423114.2023.2170256.
- [2] M. Massaro, S. Lovato, and M. Veneri, "An optimal control approach to the computation of g-g diagrams," *Vehicle System Dynamics*, 2023, doi: 10.1080/00423114.2023.2178467.
- [3] A. J. Tremlett *et al.*, "Optimal control of motorsport differentials," *Vehicle System Dynamics*, vol. 53, no. 12, pp. 1772–1794, Dec. 2015, doi: 10.1080/00423114.2015.1093150.
- [4] S. Lovato and M. Massaro, "A three-dimensional free-trajectory quasi-steady-state optimal-control method for minimum-lap-time of race vehicles," *Vehicle System Dynamics*, vol. 60, no. 5, pp. 1512–1530, 2022, doi: 10.1080/00423114.2021.1878242.
- [5] D. Casanova¹, R. S. Sharp, and P. Symonds, "Construction of race circuit geometry from on-car measurements," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 215, no. 9, pp. 1033–1042, Sep. 2001, doi: 10.1243/0954407011528590.
- [6] N. R. Kapania, J. Subosits, and J. Christian Gerdes, "A Sequential Two-Step Algorithm for Fast Generation of Vehicle Racing Trajectories," *J Dyn Syst Meas Control*, vol. 138, no. 9, Sep. 2016, doi: 10.1115/1.4033311.
- [7] S. Lovato and M. Massaro, "Three-dimensional fixed-trajectory approaches to the minimum-lap time of road vehicles," *Vehicle System Dynamics*, vol. 60, no. 11, pp. 3650–3667, Nov. 2022, doi: 10.1080/00423114.2021.1969024.
- [8] S. Radrizzani, G. Panzani, and S. M. Savaresi, "A tyre wear modelling approach for vehicle dynamics simulation and control-oriented analyses with application to

- motorcycles,” *Vehicle System Dynamics*, 2023, doi:
10.1080/00423114.2023.2232057.
- [9] H. B. PACEJKA and I. J. M. BESSELINK, “Magic Formula Tyre Model with Transient Properties,” *Vehicle System Dynamics*, vol. 27, no. sup001, pp. 234–249, Jan. 1997, doi: 10.1080/00423119708969658.
- [10] I. J. M. Besselink, A. J. C. Schmeitz, and H. B. Pacejka, “An improved Magic Formula/Swift tyre model that can handle inflation pressure changes,” *Vehicle System Dynamics*, vol. 48, no. sup1, pp. 337–352, Dec. 2010, doi: 10.1080/00423111003748088.
- [11] Y. Tezuka, “Application of the magic formula tire model to motorcycle maneuverability analysis,” *JSAE Review*, vol. 22, no. 3, pp. 305–310, Jul. 2001, doi: 10.1016/S0389-4304(01)00113-8.
- [12] A. E. Schramm, L. Leonelli, and S. Sorrentino, “Driveline Stability in Racing Motorcycles: Analysis of a Three Degrees of Freedom Minimal Model,” *Journal of Applied and Computational Mechanics*, vol. 9, no. 2, pp. 404–418, 2023, doi: 10.22055/jacm.2022.41157.3709.
- [13] S. Sorrentino and L. Leonelli, “A study on the stability of a motorcycle wheel–swingarm suspension with chain transmission,” *Vehicle System Dynamics*, vol. 55, no. 11, pp. 1707–1730, Nov. 2017, doi: 10.1080/00423114.2017.1319962.
- [14] P. Ciępką, W. Wach, and J. Zębala, “Deceleration of Engine-Braked Motorcycles,” *Machines*, vol. 11, no. 8, Aug. 2023, doi: 10.3390/machines11080812.
- [15] M. Bartolozzi, A. Boubezoul, S. Bouaziz, G. Savino, and S. Espie, “Data-Driven Methodology for the Investigation of Riding Dynamics: A Motorcycle Case

- Study,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, no. 9, pp. 10224–10237, Sep. 2023, doi: 10.1109/TITS.2023.3271790.
- [16] M. Bartolozzi, A. Niccolai, C. Lucci, and G. Savino, “Motorcycle emergency steering assistance: A systematic approach from system definition to benefit estimation and exploratory field testing,” *Accid Anal Prev*, vol. 188, p. 107116, Aug. 2023, doi: 10.1016/j.aap.2023.107116.
- [17] N. L. Merkel, “A Review on the Development of a Test Method for Motorcycle Autonomous Emergency Braking Systems,” in *The Evolving Scholar - BMD 2023, 5th Edition*, The Evolving Scholar - BMD 2023, 5th Edition, Oct. 2023. doi: 10.59490/6504cfa5777e8c1d2e265506.
- [18] G. Cassese, C. Lucci, G. Savino, and N. Baldanzini, “Analysis of the rider’s body movement during the intervention of the Autonomous Emergency Braking system for Motorcycles (MAEB),” *IOP Conf Ser Mater Sci Eng*, vol. 1214, no. 1, p. 012047, Jan. 2022, doi: 10.1088/1757-899X/1214/1/012047.
- [19] P. Huertas-Leyva, G. Savino, N. Baldanzini, and M. Pierini, “Loss of Control Prediction for Motorcycles during Emergency Braking Maneuvers Using a Supervised Learning Algorithm,” *Applied Sciences*, vol. 10, no. 5, p. 1754, Mar. 2020, doi: 10.3390/app10051754.
- [20] X. Zheng, X. Zhu, Z. Chen, Y. Sun, B. Liang, and T. Wang, “Dynamic modeling of an unmanned motorcycle and combined balance control with both steering and double CMGs,” *Mech Mach Theory*, vol. 169, p. 104643, Mar. 2022, doi: 10.1016/j.mechmachtheory.2021.104643.
- [21] R. Lobjois and F. Mars, “Effects of motorcycle simulator configurations on steering control and gaze behavior in bends,” *J Exp Psychol Appl*, vol. 26, no. 1, pp. 108–123, Mar. 2020, doi: 10.1037/xap0000241.

- [22] M. Nugent, G. Savino, C. Mulvihill, M. Lenné, and M. Fitzharris, “Evaluating rider steering responses to an unexpected collision hazard using a motorcycle riding simulator,” *Transp Res Part F Traffic Psychol Behav*, vol. 66, pp. 292–309, Oct. 2019, doi: 10.1016/j.trf.2019.09.005.