Proceedings, Bicycle and Motorcycle Dynamics 2016
Symposium on the Dynamics and Control of Single Track Vehicles,
21 – 23 September 2016, Milwaukee, Wisconsin USA

Using Simulators for the Assessment of Handling of Motorcycles

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ABSTRACT

Currently only a few motorcycle simulators exist, few or none of which are used during the development of real vehicles. Indeed, most of the existing simulators can some-how reproduce the behavior of a 'typical' motorcycle, as opposed to a 'specific' motorcycle or configuration.
In this work the motorcycle simulator of the University of Padova is employed to assess its possible usage in the development phase of real vehicles. The ultimate objective is using the simulator to evaluate the handling of a specific motorcycle in a specific configuration.
Lab tests, numerical simulations, road tests with onboard telemetry, and simulator tests have been employed during this research. The same riders that rode the real motorcycle on the real track tested the virtual motorcycle on the (same) virtual track using the simulator. Different setups were considered, both on the track and on the simulator, including different front frame properties, front wheel inertial properties, tires, lower surface friction (wet track), steering damper settings, as well as frame structural stiffness.

Keywords: PTW Simulators, Powered Two Wheelers, Motorcycle Dynamics, Handling, Virtual Reality.

1 INTRODUCTION

Currently only a few motorcycle simulators exist [1]-[5] few or none of which are used during the development of real vehicles. Indeed, most of the existing simulators can some-how reproduce the behavior of a 'typical' motorcycle, as opposed to a 'specific' motorcycle or configuration. In other words, the rider feels like he is riding something resembling a motorcycle, but it does not correspond to the behavior of a particular motorcycle model configured in a particular way. This is likely due to the fact that motorcycle dynamics include a number of challenging issues, ranging from self-excited instabilities (such as weave and wobble) to complex tire behavior where (longitudinal and lateral) slips combine with large camber angles and complex roll dynamics. As a result, instead of using a very detailed and parameterized model which would capture such effects, simplified and empirically tuned models with generic 'dummy' parameters are often preferred. While such generic simulators may be suitable for behavioral studies of riders the aforementioned simplifications preclude their use for the development of real vehicles.

The advantages that motorcycle simulators could provide to design engineers is important. It is well known that a significant portion of the development time and cost of new vehicles is driven by physical testing of actual vehicles and test rider's subjective judgments. This is because things like handling behavior of motorcycles are not easy to quantify objectively. If one aims to reduce the hours spent by test riders on the track (with related cost, safety and repeatability issues) and also minimize the need for multiple iterations of prototype hardware, the use of simulators and their human-in-the-loop analyses seems the most viable alternative.

In this work the motorcycle simulator of the University of Padova [3] is evaluated to assess its possible usage in the development phase of real vehicles. Lab tests, numerical simulations, road tests with onboard telemetry, and simulator tests have been employed during this research. As a first step, the parameters related to the geometry, mass, inertia and structural compliance of the selected motorcycle were measured through lab testing together with characterization of the selected tire sets. As a second step, a numerical motorcycle model was populated with the measured data [6]-[10]. As a third step road tests were carried out on the selected track, and results compared with those of the numerical model for validation. Next, specific track geometry and features were created in a virtual environment. As a last step, the same riders that rode the real motorcycle on the real track tested the virtual motorcycle on the (same) virtual track using the simulator. Different set-ups were considered, both on the track and on the simulator, including different front frame properties, front wheel inertial properties, tires, lower surface friction (wet track), steering damper settings, as well as frame structural stiffness.

The following paper provides a brief comparison of the real motorcycle and virtual simulator telemetry, indicates some of the key parameters affecting simulator fidelity, and suggests possible areas of improvement.

2 SIMULATOR

The simulator (Figure 1) consists of a five degree of freedom mock-up, which features lateral displacement, yaw, roll, pitch and steer. It runs a 14 degree of freedom motorcycle multibody model: chassis position and orientation, steer, front and rear suspension travel, front and rear wheel spin, engine spin, frame (lumped) deformation and sprocket absorber (lumped) deformation. The inputs of the mathematical model are measured by sensors on the mock up: steering torque, throttle position, front and rear brake pressure, clutch position, gearshift position and rider lateral position (estimated from saddle pressure sensor). The road-tire interaction model is based on Magic Formulas, which depend on tire longitudinal slip, lateral slip and camber angle. The transient behavior is accounted for using relaxation equations. The motion of the mock-up is computed from the motion of the virtual bike by an empirically tuned filter, which prevents the mock-up from exceeding the physical constraints (e.g. maximum displacements of actuators) and distributes the motion between the mock-up and the screen (e.g. in the case of the roll). The visual scenario is projected onto three 1.5m x 2m widescreens placed in front of the rider. A 5.1 surround sound system generates the environmental sounds encompassing the rider. Noise of the footpegs scraping on the road surface at high roll angles is included.

Figure 1. Motorcycle simulator - University of Padova.

3 VALIDATION

The validation of a simulator is usually divided into objective and subjective validation. The objective validation is carried out by comparison of objective quantities such as steering torque and steering angle between the simulator and the real vehicle. The subjective validation is usually based on questionnaires asking riders about their sensation when riding the simulator and the real vehicle. The subjective validation is usually the Achille's heel of the validation protocol, because it simply is not objective.

In this study the approach was to validate both the objective and subjective performance of the simulator concurrently via comparison to recent testing of the actual bike on the actual track by the same expert riders. It is important to note that these were "limit-handling" laps probing the boundaries of the vehicle's performance as opposed to more pedestrian laps (i.e. a casual speed where the rider could negotiate the course in any number of ways).

In order to justify the study all parties had to have the utmost confidence in the underlying multibody and tire model fidelity and their inputs. As mentioned vehicle and tire model parameters were measured in a laboratory and the results were examined using numerical simulation methods prior to utilizing the simulator. Also, as mentioned, the virtual environment was engineered to match the actual track as closely as possible, including track width, edge markings/curbing, grass for run-off, some level of background scenery and obviously track/turn geometry.

When riding a real or a virtual motorcycle what the rider is feeling (its "handling") is related to the vehicle's dynamics and the required inputs (mainly throttle and steer torque) and resulting outputs (steer, roll, etc.). Figure 2 shows a comparison between a road test and a simulator test in terms of speed, steer angle (positive when CW from the rider's point of view), steer torque (positive when CW), roll angle (positive when CW as seen from behind the bike) and trajectory for one of the two (professional) riders involved in the study. The speed varies in the range 35-75mph (~55-120kph), steer angle in the range ±1.5deg, steer torque between -80 (CCW) and +60Nm (CW), the roll angle in the range ±35deg, with overshoots up to 40deg in the simulator test only. A visual comparison of the data is deemed good and, to the best of the authors' knowledge, is the first of this kind presented in literature.

The relatively short track contains many dynamic events. Specifically, these can be broken down into various turns (steady state, accelerating or braking) and some transient maneuvers linking them together. The trajectory overlay proves interesting to compare the rider's trajectory on the virtual bike versus actual GPS data from the track test. Examining a few key examples on the track we can compare the correlation.

The portion of the lap from 0-500m contains both a left and a right hand corner, each at more or less steady state (constant speed). The rider is utilizing the entire available lean angle of this particular vehicle (~35deg). In real life the physical limit is likely the footboard scraping on ground while on the simulator the same scenario is replicated using a tunable audio cue. As we can see the speed, steer and roll angles are very similar between the virtual and road test. We notice the road test inputs are very crisp while those on the simulator are slightly less aggressive as the rider is "feeling out" the system. For example, at 300m the rider probes the simulator lean angle limit as well as the track boundary (as seen on the trajectory plot) as opposed the test track where the bike is held at full lean with some distance to the curbing.

As the lap continues the subsequent maneuvers become somewhat more daunting. At 550m we witness an aggressive right turn entry where simulator and track data match very closely. Similarly exiting the same corner at 900m the torque, as well as the speed trace, attained by the rider of the virtual bike closely mimics that achieved during road test. Trajectory comparison in this segment is quite good.

The track section from 900 to 1000m represents aggressive "trail braking" (i.e. varying brake pressure during cornering). Immediately after the rider straightens up the vehicle they must slow by "trail braking" into a fairly tight right-hand corner. Here the road test data shows a second torque spike which is likely the rider reacting against the inertia of the vehicle while trying to redirect it into the next maneuver. Following this aggressive transient, at about 1000m, we notice some slight oscillation in the simulator likely due to the system response of the simulator mockup driving extraneous steering torque into the virtual model.

The lap continues with a left-to-right corner combination, again at max lean angle. From 1200 to 1400m we notice the steering torque of the road test is a bit higher than the simulator. This is likely due to the tighter trajectory of the road test, maintaining more roll angle deeper into the chicane. At about 1380m, the rider transitions the vehicle via a rapid transient achieving a roll rate of ~100deg/s. Again we notice some oscillation in steer angle, torque and roll as the simulator overshoots slightly. In this case the rider overestimated the input needed by the virtual bike and as a result the trajectory goes slightly inside the corner. After a brief acceleration, matching closely between both road and simulator tests, the rider enters the final right hand corner thus completing the lap.

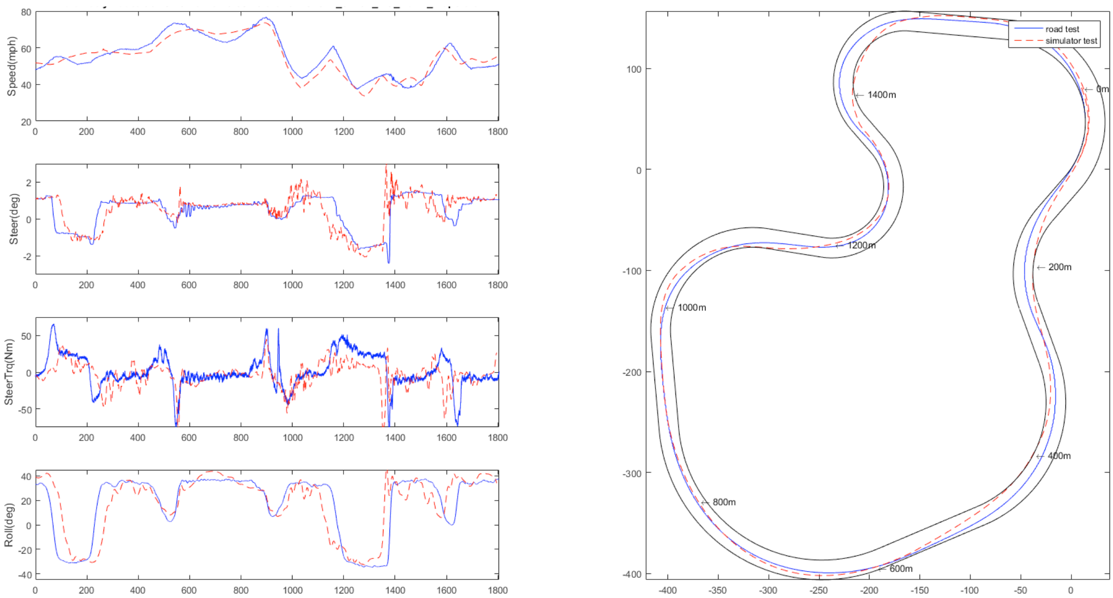

Figure 2. Road test vs simulator test.

4 PARAMETRIC ANALYSIS

Once the basic handling performance of the simulator has been proven out against the actual road test, it becomes a tool for changing various vehicle parameters quickly and easily. In this study different set-ups were considered, both on the track and on the simulator, including different front frame properties, front wheel inertial properties, tires, lower surface friction (wet track), steering damper settings, as well as frame structural stiffness. Indeed, the ultimate goal would be to use the simulator as a tool to investigate different set-ups in order to consolidate or eliminate resource-intensive, on-track configurations. It is worth stressing that, compared to a PC-based simulation approach already used by engineers to optimize vehicle setups; the simulator concept offers the opportunity the put the human-in-the-loop to actually feel how different configurations handle. This is particularly useful as some of the nuanced PTW vehicle performances, like handling, are still difficult to capture objectively.

Highlights from a subset of parameters investigated by use of the simulator are reported below. The plot format is maintained, showing pertinent vehicle dynamic quantities as well as trajectory overlay. However, focus is placed only on subsections of track relevant to that parameter's effect.

Front wheel spin inertia - It has been established that transient maneuverability is primarily related to front wheel spin inertia. Namely higher front wheel spin inertia leads to lower transient maneuverability as the rider acts to oppose the gyroscopic moment generated by the roll precession [11]. While previous track tests were conducted to support this principle, the simulator makes such parametric analysis much easier.

Maintaining all other vehicle parameters equal the front wheel spin inertia of the simulator's virtual bike was varied plus and minus 20%. Results are shown in Figure 3 and 4 respectively. Note that in these plots the road test data shown is for the reference vehicle with nominal front wheel spin inertia (as depicted in Figure 1 from approximately 1200 to 1500m).

Focusing strictly on this transient maneuver as shown in Figure 3 (+20% wheel spin inertia) one can observe a larger magnitude negative torque peak around 1400m followed by a lower resulting roll rate (slope of the roll angle) with respect to the reference vehicle.

Reducing front wheel spin inertia by 20% (Figure 4) one can observe that the rider applies roughly the same torque magnitude as the reference vehicle but is somewhat surprised by the response. The steering angle peak of 4deg into the right corner overshoots the reference case while the trajectory momentarily tracks inside. The rider applies a positive steering torque (CW) in an attempt to arrest the roll angle.

Although this is a transient maneuver between left and right cornering as opposed to a true lane change, the Lane Change Roll Index (LCRI) can still be computed:

$$LCRI=\tau_{p\text{-}p}/\omega_{p\text{-}p}V_{avg} \tag{1}$$

where $\tau_{p\text{-}p}$ is the peak to peak steer torque, $\omega_{p\text{-}p}$ is the peak to peak roll rate and V is the average speed during the manoeuver. Table 1 reports this handling metric for all three simulated test cases.

Table 1. Comparison of transient maneuvrability using LCRI.

Front wheel spin inertia	LCRI [N-s^2/rad]
+20%	2.54
Nominal	1.90
-20%	1.51

Subjective impressions of these tests correspond with the results shown above, i.e. heavier efforts and slower response for the higher wheel inertia and vice versa respectively. It should be noted that the timeframe of changing these parameters and running the simulator test is significantly less than changing or modifying an actual front wheel on a test vehicle and requires no prototype hardware or tools.

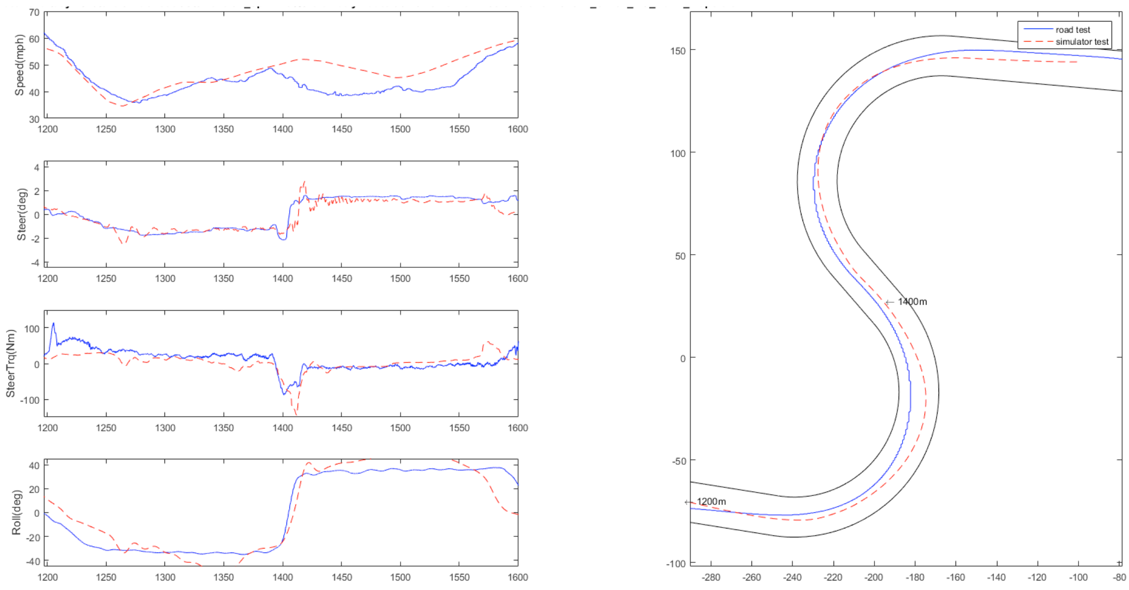

Figure 3. Simulator test with increased (+20%) front wheel spin inertia vs. nominal road test.

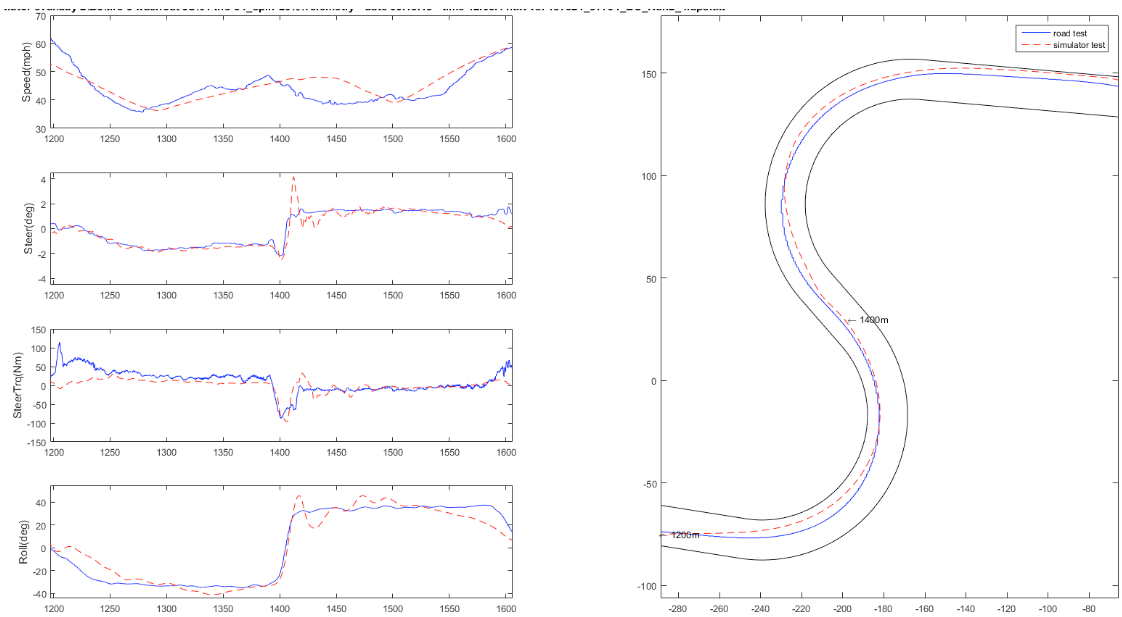

Figure 4. Simulator test with reduced (-20%) front wheel spin inertia vs. nominal road test.

Wet track - Another interesting possibility with a simulator is to change the track or environment at the click of a button. In this case the riders thought it would be interesting to test the vehicle on the same track but in wet conditions. This was achieved by essentially lowering the peak friction coefficient of the associated tire model parameters. Examining the first 800m of the track (see Figure 5) a number of interesting observations can be made. As expected, we notice that the speeds and consequently the roll angles are lower. While the steering angle trace remains largely unchanged the rider significantly reduces their peak torque inputs and takes a slower, more conservative trajectory around the course. This correlates well to how one would likely drive in wet conditions, going slower, leaning the bike less, i.e. being generally more conservative. In reality this behavior is driven by constraints imposed on the rider by the environment which is in this case virtual.

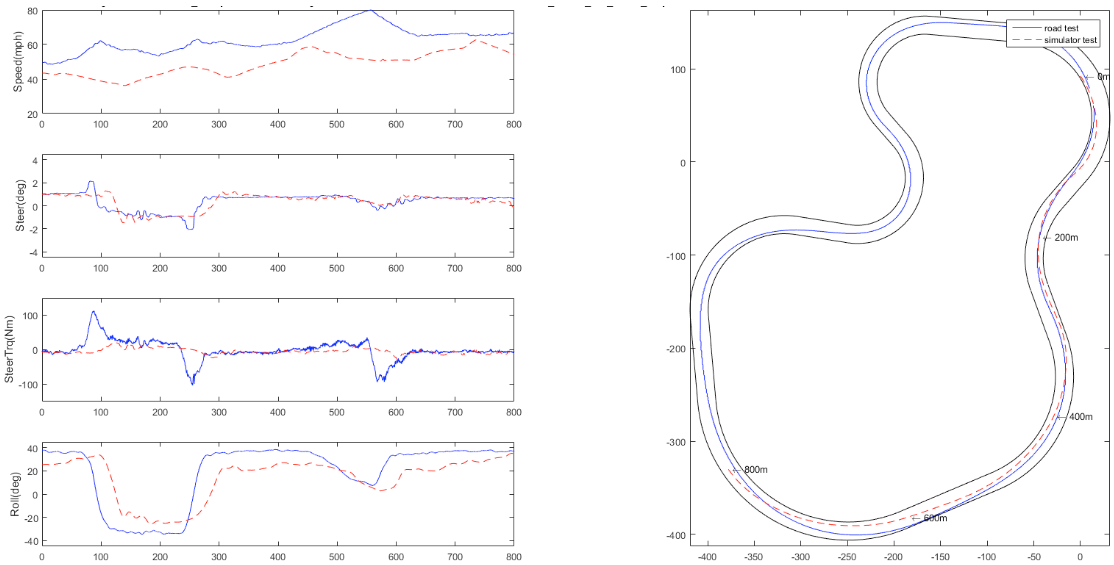

Figure 5. Simulator wet test vs. dry track test reference data

Parametric studies varying tire sets, steering damper settings as well as front frame mass and structural stiffness were also carried out on the simulator. Generally, results correlated with the subjective impressions experienced by the same riders during previous track testing. However, the magnitude of these effects on handling were quite small (both in the simulator and on the real bike) and likely only perceptible to the expert test rider.

5 CONCLUSIONS

Results of this study suggest that the proposed method to objectively and subjectively validate a motorcycle riding simulator are most interesting and useful. Specifically comparing simulator performance to recent testing of an actual bike on an actual track by the same expert riders offers insight into simulator performance as well as vehicle design.

Generally favorable results suggest that high-fidelity simulators such as the one employed in this study, with adequate degrees of freedom and commensurately accurate vehicle and tire models have great potential for vehicle development. Testing or at least factor screening in the virtual environment with an (expert) human-in-the-loop can save time and money with better experimental control. This approach allows testing and/or demonstrations to occur in a safe, interactive and realistic VR environment. Scenarios difficult to achieve in the real world can quickly and easily be evaluated virtually as in the case of the wet track.

As mentioned the current study went beyond using a simulator to asses basic driving of a generic motorcycle. It is the authors' and riders' perspective that including the roll degree of freedom as well as counter-steering behavior is the base set of criteria that set motorcycle dynamics apart for other vehicle platforms. Incorporating these features into even the most basic simulators would likely benefit behavioral studies.

As shown here in order to perform vehicle handling development a simulator needs significant actuation and sensitivity as well as decent range of motion. As seen in this study torque peaks of 80Nm with steady state turn values of only ±4Nm are not uncommon. Various strategies exist for convincing the rider of the perceived roll, pitch and yaw however this study suggest fullscale (one-to-one) motion is not requisite to achieve high fidelity if the appropriate scenarios/cuing are chosen.

Two elements of the virtual environment proved particularly critical. First, isolating the rider from external distraction thus allowing the simulator to be truly immersive is important. During one test it was observed that any external distraction such as a comment from an observer profoundly affected the rider's bandwidth/workload and ability to focus on the virtual riding experience. Secondly the means and amount of cuing are important for conveying realism. The auditory cue of lean angle limits, the engine revving, even wind or wind noise were helpful if done well and a hindrance if applied in excess. Careful design of visual and motion cuing (such as the peripheral screens and visual roll augmentation) are paramount to avoiding simulator sickness. That being said, after nearly three days of testing on the simulator, neither motorcycle pilot experienced sickness.

Although results of this study were generally favorable the following areas were cited for improvement:

- Adapting the ergonomics of the simulator buck (mock-up) to match that of the actual test bike is critical as the way in which riders input torque (i.e. how much leverage they have as well as the anthropometric joint angles) influences rider biomechanics and perceived effort. This can be accomplished either through an adjustable rig or through a dedicated buck for each bike being studied.
- The current simulator was able to sustain the limit-handling nature of this testing however abrupt transients with very high steering torque inputs suggested slight improvements could be made to its structural rigidity. The electromechanical actuation was tested to its limits and worked well even in this study.
- Starting from a stop was not part of the current testing. That particular function still proves daunting to many motorcycle simulators. The current simulator employs a rolling start to avoid a need for artificial stabilization.
- Although seat and foot-pegs loading/inputs were not that important on this particular bike (due to large vehicle to rider mass ratio and relaxed riding posture) it may be more important for sport riding posture/movements.
- Although the virtual environment was sufficient to yield a high level of test fidelity it would be interesting to try some of the most recent advances in VR goggles. Specific to motorcycles, this might offer the added benefit of not only capturing to the side-view peripherals but also the pronounced visual effect of a road surface moving beneath the rider.

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