Recent studies have identified roadside safety barriers as a cause of severe injuries and fatalities for motorcyclists. Roadside safety barrier have traditionally been designed with limited consideration for motorcyclist safety since the primary focus was on the safety of occupants of enclosed vehicles. Computer simulations of full-scale crashes between motorcyclists and road barriers would provide valuable support to improve the limited knowledge of the interaction between motorcyclists and barriers during a crash as well as assess any proposed design countermeasure to reduce serious injuries and fatalities.

This study aimed to develop a Finite Element (FE) model of a sport-touring motorcycle that may be used to investigate in detail the characteristics of upright impacts between motorcyclists and different types of roadside safety barriers. Verification and validation was performed on the critical components of the developed motorcycle model, such as the steering system and the front/rear suspensions. Validation against a full-scale crash test involving a concrete safety barrier was also performed to assess the overall response of the modeled motorcycle in combination with an ATD model during a crash. The promising results obtained using the developed motorcycle FE model provided an initial level of confidence for using it in future applications aimed at investigating crash scenarios involving roadside safety barriers and motorcycles.

INTRODUCTION

Motorcycle crashes into roadside safety barriers

In Australia, motorcycles account for 4.4% of total vehicle registrations, yet approximately 17% of all motor vehicle fatalities involve motorcyclists. Such statistics, which are similar for most other countries, clearly indicate the higher risks to which motorcyclists are subjected compared to other road users. Recent studies in both Australia and USA have identified roadside safety barriers as a possible cause of severe injuries and fatalities for motorcyclists (1-4).
Roadside safety barriers can effectively protect motorists from impacting fixed objects and various hazards located along the side of the road and are designed to reduce the potential for serious injuries when impacted by an errant vehicle (5). However, their design has traditionally had limited consideration for motorcyclist safety since primary focus was on the safety of vehicle occupants, which are by far the category with the largest representation of all the road users seriously injured and killed. Nonetheless, based on the safe-system approach for a safer road transport system, which has been adopted in many countries worldwide, impacts into roadside safety barriers should become a forgiving event for all road users, including motorcyclists. Further, recent consideration for motorcyclists safety in the design of roadside safety hardware has started to grow due to the concerning increasing percentage of motorcyclist fatalities relative to the total number of road deaths (6, 7).

Motorcyclist crashes into roadside safety barriers can be classified in two main typologies, depending on the rider posture at impact: (a) motorcyclist riding into the barrier at an upright riding position or (b) rider sliding into the barrier after being already separated from the motorcycle. Likely, different injury mechanisms may be associated with each of these two rider postures. Previous analyses indicated that either of the two mentioned crash postures appear to be equally distributed in real-world crashes between motorcyclists and roadside safety barriers in Australia and New Zealand as well as in Europe (2, 8). However, it is predicted that the effectiveness of recently introduced active systems for improving motorcycle stability during critical maneuvers, such as the Motorcycle Active Braking System (MABS), would likely shift the majority of those motorcycle crashes that are still unavoidable to occur in an upright riding position once these new technologies would reach full market penetration (9, 10). Thus, it is likely that also the majority of motorcyclist crashes into roadside safety barriers in the future will mainly occur while the rider is straddling the motorcycle in an upright riding position.

So far, standard testing procedures for assessing the safety performance of roadside safety barriers in a crash involving a motorcyclist have been developed exclusively in Europe. The majority of these standard testing procedures, which are either European or national standards, have been focused solely on the case of a rider sliding on the road after it has already been separated from the motorcycle (11-13). The only exception is a crash test protocol developed by the German Federal Highway Research Institute, BASt, which considers an impact of an upright motorcyclist into the tested barrier (14, 15). Therefore, only a limited number of non-standardized full-scale crash tests have been performed so far to investigate the performance of a motorcyclist crashing into various types of roadside safety barriers in an upright riding posture (8, 10).

Computer simulations of full-scale crashes would provide a valuable support to improving the limited knowledge regarding the interaction between motorcyclists and roadside safety barriers, especially for the case of an upright crash posture. Further, simulations may also support engineers in assessing any future proposed design countermeasure to reduce the injury risks associated with motorcyclist crashes into barriers. Most of the existing numerical models of motorcycles have been developed to assess the rider kinematics and dynamics during crashes into another vehicle (16, 17). Such scenario does not require specific modeling of the motorcycle kinematics, especially in terms of suspension behavior. Limited modeling efforts have been performed to specifically simulate impacts of motorcyclists into road safety barriers in an upright riding position. As an example, simplified multibody models of a motorcycle and rider were previously used to perform a basic analysis of a rider head-on impact into a deformable guardrail (18) or angled impacts into wire-rope and concrete safety barriers (8). Further, a Finite Element
(FE) approach would be preferred to model the motorcyclist deformable body and thus simulate more realistically any loads applied to the rider during an impact into a barrier. The only motorcycle FE model that was developed to assess the interaction between motorcyclists and road safety barriers was based on a simplified moped-style motorcycle. That model was used as a bullet vehicle (without a rider model) in simulations aimed to perform a preliminary assessment of a novel design of a motorcycle-friendly barrier (19).

Objective and methods

This study aimed to develop a FE model of a motorcycle that may be used to investigate in detail the impact characteristics between motorcyclists and different types of roadside safety barriers when impacting in an upright riding posture. Since a previous study identified that touring motorcycle riders have a higher tendency to collide with barriers in an upright posture (1), a sport-touring motorcycle was selected as the most appropriate two-wheel vehicle to be modeled.

Initially, the geometry of each relevant component of a sport-touring motorcycle was digitally acquired using a three-dimensional scanner. The motorcycle FE model was then developed and the proper functionality of critical modeled components such as the steering system and the front/rear suspensions was verified. Finally, the model was validated against experimental tests with the motorcycle traversing various sloped obstacles as well as against a previously performed full-scale crash test into a concrete safety barrier.

MOTORCYCLE FE MODEL

Model development

The model was developed for use with the non-linear FE solver LS-DYNA, which is highly suitable to simulate impact events (20). It replicated in detail the geometry and mass of a 2008 Suzuki GSX-650F motorcycle, which is well representative of modern sport-touring motorcycles with the rider sitting in an upright posture. Both the actual motorcycle and the developed FE model are shown in Figure 1.

The major motorcycle structural components as well as any other non-structural parts that may interact with a road safety barrier and the rider during a crash and, thus potentially affect their kinematics and dynamics, were explicitly modeled. The geometry of the selected components of the actual motorcycle was initially digitized using a 3D laser scanner and the obtained surfaces were then used as a basis to create the FE mesh. Most components were modeled using shell elements with the exception of a few bulky parts, such as the engine, the radiator, and the brake calipers, which were modeled using solid elements. The motorcycle truss frame served as the main structure, with all the other modeled components connected to it using rigid links of various types, depending on the specific degrees of freedom of the actual connection.

Both the front and rear suspensions were modeled in detail. The paired upper and lower forks of the front suspensions were explicitly modeled using shell elements. A cylindrical-type kinematical joint was defined between each pair of upper and lower forks to allow the suspension to either compress or extend. The upper and lower forks were then connected by separate discrete spring and damper elements, which modeled the coil spring and the damper of
FIGURE 1 Suzuki GSX-650F motorcycle – actual motorcycle and FE model.

The actual front suspension, respectively. Each of the two triple clamps that connect the two upper forks in the actual front suspension was approximated as a rigid constraint between the modeled upper forks.

The swingarm of the rear suspension system was explicitly modeled using shell elements. A kinematical joint was used to model the actual hinge between the swingarm and the frame. The rear suspension cushion-lever-rod assembly was then modeled using two dummy elements connected through a series of rigid kinematical joints that replicated the kinematics of the actual assembly, as shown in Figure 2.

The end of the cushion lever that is connected to the shock absorber was modeled as a rigid element, A, which was hinged relatively to the frame at a position equivalent to the pivot location in the actual cushion lever. The ends of the two parallel cushion rods that are connected to the swingarm were modeled using another rigid element, B, which was hinged relatively to element A at a location corresponding to the rods’ actual hinge to the cushion lever. Finally, the center of the element B was hinged relatively to the swingarm. The spring-shock-absorber assembly of the actual rear suspension was modeled using a parallel combination of discrete spring and damper elements, which were defined between element A and an appropriate location of the frame.

The stiffness of the coil springs that are located inside each fork of the front suspension and in the rear suspension assembly was measured through compression tests conducted by a specialized laboratory. The force-velocity characteristic curve of the damper of the rear suspension was measured as well. Unfortunately, the damping curve for the front-suspension

FIGURE 2 Cushion-lever-rod assembly: actual system (Left), equivalent kinematical system (Center), FE modeled system (Right).
forks could not be measured due to a dimensional limitation of the testing machine. The geometry of the developed model was based on the standing motorcycle when balanced under gravity. Thus, to account for the weight of the motorcycle, appropriate pre-compression values were assigned to the discrete spring elements used to model the front and rear suspensions. For both front and rear suspensions, two additional discrete elements acting as a compression and an extension stopper, respectively, were also modeled.

Both the rim and the tire of the front and rear wheels were modeled using shell elements, whereas solid elements were used for the wheel hubs. For each tire, an LS-DYNA airbag definition was used to assign the internal pressure within the volume enclosed by the tire and the rim circumferential surface. Finally, all the other components of the motorcycle that could interact with the rider or the road safety barrier during a crash such as front and rear brake discs and calipers, fairings, radiator, handlebar, fuel tank, seat, engine case, foot pegs, and exhaust were explicitly modeled as well.

The location of the actual motorcycle center of gravity along the longitudinal and vertical directions was experimentally measured before the motorcycle was disassembled. In order to match the location of the motorcycle center of gravity, lumped-mass elements were added to the motorcycle model to compensate for any other non-relevant components that were not explicitly modeled as well as for the various fluids.

**Model verification**

**Front and rear suspensions**

An initial verification of the proper kinematics of both front and rear suspensions was carried out. To facilitate the verification of both suspension systems up to their compression limit, their stiffness and damping were zeroed while the motorcycle model was left free to settle under the effect of gravity onto a rigid surface. Also, to prevent the motorcycle model from tilting on either side, its frame was constrained in the vertical plane. The simulated displacement of both the front and rear suspensions is shown in Figure 3(a). Both suspensions replicated the expected kinematics while the motorcycle settled under gravity and eventually reached a stop at the defined limit displacement equal to 130 mm (5.1 in.) and 38 mm (1.5 in.) for the front and the rear suspensions, respectively.

The overall dynamic response of the front and rear suspensions was also verified by simulating the response of the motorcycle model when riding over a 100-mm high bump at 20 km/h. A 75-kg (165-lb) lumped mass was added to the motorcycle center of gravity to model the mass of the rider. Both modeled suspensions proved to be capable of simulating the typical dynamic behavior expected when traversing a bump, as shown in Figure 3(b). The front and rear suspensions compressed allowing the respective tire to maintain constant contact with the bump and the bike to remain stable while traversing the bump.

**Steering**

The proper kinematics of the steering system was verified for rotations in both directions over the maximum steering range. The motorcycle frame was fully constrained and a steering torque was induced by applying a 50-N (11-lbf) force at the most forward location of the front-wheel rim. A plot of the wheel rotation along the steering axis for the case of a right turn is shown in
Figure 4(a). The front wheel steered properly and came to a stop at the desired maximum angle of 32 degrees.

The functionality of the steering to turn the motorcycle model when it is travelling was also verified. In this case, a gradual rotation of the steering was imposed while the motorcycle model was travelling along a straight trajectory at an initial speed of 30 km/h (18.6 mph) on a flat rigid surface. Upon application of a steering input, the motorcycle model, which was initially leaning on its left side by 30 degrees, gradually transitioned its trajectory along a curve path and started to lean towards the external side of the curve due to the centrifugal force, as shown in the sequence in Figure 4(b). The motorcycle kept leaning to the external side of the curve, until its right side eventually impacted the ground surface at completion of a quarter turn.

FIGURE 3 Suspension verification – behavior with stationary and moving motorcycle.
FIGURE 4  Steering verification – behavior with stationary and moving motorcycle.

MODEL VALIDATION

Motorcycle response to sloped obstacles

During a crash into a road barrier with the motorcyclist riding in an upright position, the motorcycle front wheel is likely to be the first component to impact. For crashes into a safety-shape barrier, the front wheel of the upright motorcycle will initially impact the protruding slope at the bottom of the barrier. This slope, which is shallower than the barrier upper slope, is designed to mitigate the vehicle deceleration at the beginning of the impact by initially compressing the suspension of the impacting front wheel and inducing a subsequent vehicle lift so that part of its kinetic energy is converted into gravitational potential energy. Since a lift of the vehicle would facilitate its redirection, it is important that the motorcycle model could accurately predict this critical initial interaction between the front wheel and the bottom slope of a safety-shape barrier. Thus, the model was validated against experimental tests specifically performed to
assess the kinematics of the motorcycle and the front suspensions during an impulsive event involving slopes.

Setup of experimental and simulated slope tests

A series of experimental tests were conducted with the actual Suzuki motorcycle traversing various sloped obstacles. In these tests, a rider maneuvered the motorcycle over 200-mm (7.9-in) high sloped obstacles at initial nominal speeds varying between 15 km/h (9.3 mph) and 20 km/h (12.4 mph). The details of each tested configuration are shown in the test matrix in Table 1. Two levels of slope steepness were tested, equal to 20 deg and 45 deg. For the case with a 20-deg slope, both a 90-deg (i.e., head-on) and a 45-deg approach angle were tested; whereas in the case with a 45-deg slope only a 90-deg approach could be safely tested by the rider. In all tests, the displacement of the front suspension right fork and the rear suspension swingarm were measured using string potentiometers. For repeatability purpose, each scenario was tested a minimum of three times.

The plots of the measured displacements for all the tests are shown in Figure 5. Note that, in the tests with a head-on approach, the motorcycle front suspension underwent some undesired oscillation due to smooth irregularities of the pavement along the approach path to the ramp. Gradually increasing initial segments indicated by the dashed lines in the relevant graphs show how those curves would have been without the initial pre-compression that was caused by those undesired oscillations.

Experimental and simulated kinematics of the motorcycle and suspension system

As an example, the simulated and experimental motorcycle kinematics for the case with a 20-deg slope and 45-deg approach direction is compared in Figure 6. The motorcycle kinematics simulated using the developed FE model coupled with the ATD was in most part in good agreement with the experimental results. The details of each tested configuration are shown in Table 1. Two levels of slope steepness were tested, equal to 20 deg and 45 deg. For the case with a 20-deg slope, both a 90-deg (i.e., head-on) and a 45-deg approach angle were tested; whereas in the case with a 45-deg slope only a 90-deg approach could be safely tested by the rider. In all tests, the displacement of the front suspension right fork and the rear suspension swingarm were measured using string potentiometers. For repeatability purpose, each scenario was tested a minimum of three times.

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FIGURE 5  Slope tests - displacement of front forks and rear swing arm for repeated tests.

FIGURE 6  Slope tests - simulated and experimental motorcycle kinematics with 20-deg slope at 45-deg approach angle (Test 20/45-3).
agreement with what observed during the experimental test. The simulated motorcycle pitching when traversing the slope as well as the dynamic behavior of both front and rear suspensions closely matched the test. A comparison of the experimental and the simulated deflection of the front and rear suspensions for all the three simulated scenarios is shown in Figure 7.

In general, the simulated compression of the front suspensions was in good correlation with the experimental measurements for all the three tested scenarios. However, a fair correlation was only obtained for the rear suspension (i.e., the simulated deflection of the rear swingarm). The rear suspension underwent two distinct compression peaks. The initial compression peak was caused by the motorcycle pitching up when the front wheel rode over the ramp; whereas the subsequent compression peak occurred when the rear wheel climbed over the ramp. In both cases, the simulated compression of the rear suspension occurred earlier than in the experimental tests and was also smaller in magnitude. Both these aspects of the rear suspension response could be significantly influenced by the timing and intensity of the rider body movements. During the tests, the human rider instinctively pro-actively readjusted his body in order to stabilize the motorcycle. The simplified movements that were imposed to the ATD model in the simulations could not entirely replicate such complex adaptive response of the human rider. Detailed modeling of an active rider would be a major effort per se and was not part of this research scope. Since the major focus of this validation activity was that of assessing the response of the motorcycle front suspension, the fair simulated response for the rear suspension was not considered as a major issue.

A quantitative comparison between the experimental and the simulated response of the front and rear suspensions was also assessed using the Sprague&Geers (SG) and the Anova metrics that are proposed in the National Cooperative Highway Research Project (NCHRP) Report 179 (21) for the verification and validation of numerical models in the field of roadside safety. The values of these comparison metrics, which were calculated using the RSVVP software (22), are shown in Figure 7.

The SG metric components were within the proposed acceptance scores for any of the three simulated test scenarios. However, the Anova metrics were larger than the proposed limits. For two of the three considered scenarios, in the case of the front suspensions the average of the normalized residuals was slightly larger than the suggested 5% limit. For the case of the rear suspension system, the values of the Anova metrics further exceeded the acceptance criteria. In general, both the SG and the Anova metrics indicated that the simulated response of the front suspension system was in better agreement with the experimental results than in the case of the rear suspension.

**Full-scale crash into a safety-shape barrier**

The developed motorcycle FE model coupled with the ATD FE model was used to simulate a previous crash test involving an upright motorcycle impacting into a concrete safety barrier. The accuracy of the simulated interactions between the motorcycle, ATD and barrier model was assessed.

**Setup of experimental and simulated crash test**

The crash test was conducted at DEKRA using a sport-touring motorcycle and a Hybrid III ATD (23). The test involved an impact between a Kawasaki ER-5 Twister and an 810-mm (32-in) tall
A comparison of the main specifications for the Kawasaki ER-5 and the modelled Suzuki GSX-F650 is provided in Table 2.

Although the tested Kawasaki ER-5 and the Suzuki GSX-F650 were generally similar, their designs were characterized by some intrinsic differences. The Kawasaki ER-5 was slightly smaller than the modelled motorcycle and, consequently, it was also about 41 kg (90 lb) lighter. Given the intrinsic geometrical differences in the design of the two motorcycles, the mass of the modelled Suzuki motorcycle was not reduced to limit any undesired consequent changes to its moments of inertia.

The ATD FE model previously used for simulating the slope tests was seated on the motorcycle model with an initial posture similar to that of the actual ATD at the beginning of the crash test. A model of the New-Jersey shape barrier was assembled to replicate the tested barrier curved configuration, which was reconstructed from an analysis of the images available in the test report.

**FIGURE 7** Slope tests -simulated and experimental displacement of front/rear suspensions.
### TABLE 2 Specifications of Motorcycle used in Experimental and Simulated Crash Test

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>1998 Kawasaki ER-5</th>
<th>2008 Suzuki GSX-F650</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm) [in]</td>
<td>2,070 [81.5]</td>
<td>2,130 [83.9]</td>
</tr>
<tr>
<td>Width (mm) [in]</td>
<td>730 [28.7]</td>
<td>760 [29.9]</td>
</tr>
<tr>
<td>Max Height (mm) [in]</td>
<td>1,070 [42.1]</td>
<td>1,225 [48.2]</td>
</tr>
<tr>
<td>Seat Height (mm) [in]</td>
<td>800 [31.5]</td>
<td>760 [29.9]</td>
</tr>
<tr>
<td>Wheelbase (mm) [in]</td>
<td>1,430 [56.3]</td>
<td>1,470 [57.9]</td>
</tr>
<tr>
<td>Ground Clearance (mm) [in]</td>
<td>125 [4.9]</td>
<td>130 [5.1]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tires</th>
<th>1998 Kawasaki ER-5</th>
<th>2008 Suzuki GSX-F650</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Tire</td>
<td>110/70-H17</td>
<td>120/70-ZR17</td>
</tr>
<tr>
<td>Rear Tire</td>
<td>130/70-17</td>
<td>160/60-ZR17</td>
</tr>
</tbody>
</table>

| Mass             | 1997* [434]         | 238 [524]            |
| Weight* (kg) [lb]|                     |                      |

* Weight of test vehicle including instrumentation

**Experimental and simulated kinematics of motorcycle and ATD**

A visual comparison of the simulated and experimental kinematics of both the motorcycle and the ATD for each major critical event that occurred during the crash test is shown in Figure 8. Initially, the motorcycle front wheel hit the barrier bottom slope with a consequent compression of the front suspension. Immediately after this first impact, the front wheel started to climb over the slope, thus inducing the motorcycle to pitch up. Subsequently, the deceleration due to the friction between the sliding upright motorcycle and the barrier upper slope caused the rear wheel to also lift off the ground. The motorcycle deceleration also caused the ATD to be displaced both forward and sideways towards the barrier. When the motorcycle rolled toward the barrier and impacted its top edge, the ATD leaned over the barrier with its right leg being crushed between the motorcycle and the barrier surface. The impact of the motorcycle exhaust against the barrier then caused the rear wheel to be pushed away from the barrier, while the front suspension right fork kept sliding along the barrier edge. Consequently, the ATD separated completely from the motorcycle and become airborne over the barrier. The ATD right leg impacted back onto the barrier top surface and kept sliding along it until the ATD fell completely off the back of the barrier.

In general, the FE model proved to be capable of replicating the motorcycle and ATD behavior in a reliable manner. Also the simulated ATD kinematics compared generally well against that of the actual ATD during the test; however, some differences between the simulated and experimental ATD kinematics could be noticed as well. In the simulation, the ATD separated from the motorcycle earlier than in the test and it was also thrown slightly higher over the edge of the barrier. Both these two minor differences between the simulated and experimental ATD kinematics could be potentially caused by some intrinsic geometrical and inertial differences between the tested and modeled motorcycle (i.e., Kawasaki ER-5 Twister versus a modeled Suzuki GSX-650F). Also, the motorcyclist protective clothing (i.e., jacket, pants, boots, and gloves) worn by the ATD in the experimental test likely contributed to make its response slightly stiffer. The lack of this protective garment in the modeled ATD may have then allowed for the faster ATD simulated response compared to the experimental test.
A qualitative and quantitative comparison of the simulated and experimental motorcycle resultant accelerations that were measured at the top of the steering column and under the seat is shown in Figure 9. The simulated peak accelerations at both bike locations matched within a reasonable tolerance the corresponding experimental peak values.

Overall, the simulated resultant acceleration at the steering column was in good correlation with the experimental acceleration, as also indicated by the value of the SG metric components. Only the anova average slightly exceeded the suggested 5% acceptance criterion.

However, the predicted acceleration at the seat location was larger than the experimental acceleration both at the beginning of the impact and between 250 ms and 400 ms. This resulted in the M and C components of the SG metric for the seat resultant acceleration to exceed the acceptance criteria suggested in NCHRP Report 179. The mentioned differences in the simulated and experimental resultant acceleration at the seat location may have been caused by intrinsic
geometrical differences between the modelled Suzuki motorcycle and the tested Kawasaki ER-5. Ultimately, these geometrical dissimilarities may have caused some localized, but relevant, differences between the simulated interaction of the motorcycle model with the front and top surface of the safety barrier and the actual test.
DISCUSSION AND CONCLUSIONS

A detailed FE model of a Suzuki GSX-650F sport-touring motorcycle was developed for simulating upright impacts into roadside safety barriers when coupled with a model of a straddling ATD. Initially, modelled features that are relevant for simulating an impact into a roadside safety barrier, such as steering and suspension kinematics, were verified. Validation of the model was then carried out against experimental tests involving slope obstacles as well as a crash test into a concrete safety barrier.

Overall, the simulated response of the developed motorcycle model showed a promising level of confidence for future applications aimed at simulating a variety of crash scenarios involving roadside safety barriers. The motorcycle model proved to be capable of replicating in a reliable manner the kinematic response of a sport-touring motorcycle when traversing sloped obstacles as well as in a full-scale crash into a curved concrete barrier. The simulated resultant acceleration at the motorcycle steering column was in good correlation with the experimental acceleration measured in the full-scale crash test. Localized differences between the simulated and the experimental acceleration measured at the seat location were likely caused by inherent geometrical differences between the modeled and the tested motorcycles. Further, the simulated kinematics of the ATD model that was coupled with the motorcycle replicated the general behavior of the actual ATD during the full-scale crash test into the barrier. This motorcycle FE model will provide researchers with a useful tool to improve the understanding of the interaction of motorcyclists during upright collisions into roadside safety barriers, allowing to complement the limited real-world crash data currently available.

Future work should consider validating the predicted ATD dynamic loading during a full-scale crash test. Validation of the model for crashes into semi-rigid and flexible roadside safety barriers, such as guardrails and cable barriers, may be considered as well.

ACKNOWLEDGMENTS

The authors kindly thank the staff at the Crashlab testing facility of the Roads and Maritime Services of New South Wales for providing the testing instrumentation used in the experimental tests for the validation of the FE model suspension system. Acknowledgments go also to Mr. Cameron Peacock for manufacturing the wooden structures and helping with the execution of the tests. Finally, the authors would like to also thank DEKRA for providing the results of the experimental full-scale crash test with the concrete barrier. All the simulations were run on the Linux computational cluster Katana from the Faculty of Science at UNSW Australia.

REFERENCES


23. DEKRA. Anprall-Versuche mit Motorrädern an Passiven Schutzeinrichtungen [Crash Tests of Motorcycles into a Passive Safety Barrier: Upright-Propelled 1998 Kawasaki ER-5 Twister Against a 0.81-m Tall Unilateral Concrete Barrier]. Report of Test SH 99.06, Department of Accident Research/Crash Centre, 1999.