933133

Motorcycle Crash Test Modelling

J. J. Nieboer, J. Wismans, A. C. M. Versmissen, and M. T. P. van Slagmaat
TNO Crash-Safety Research Centre

I. Kurawaki and N. Ohara
Yamaha Motor Co., Ltd.

ABSTRACT

This paper concerns the development and validation of a three-dimensional mathematical model representing a motorcycle with rider. As part of this development, several motorcycle to barrier tests were performed at the laboratories of the TNO Crash-Safety Research Centre and several measurements were carried out, including measurements to determine the inertia properties of the motorcycle segments. Results of two full scale tests involving a passenger car were then applied to validate the model in a more realistic crash environment.

The resulting MADYMO motorcycle model consists of 7 bodies linked to each other by joints and spring-damper type elements. Special attention was given to the mathematical representation of front fork, front wheel and gastank. A 50th %ile Part 572 dummy with pedestrian pelvis and legs represented the rider. For representation in the model an existing dummy database was updated.

Computer simulation of motorcycle rider behaviour during a collision event proved to be far more difficult than the simulation of passenger car occupants, due to the contact interaction between three moving ojects and the complex way in which motorcycles and their riders behave after impact. Nevertheless, the simulation results obtained are very promising. The main drawback of the simulation model as presented here seems to be the underestimation of the energy absorption by the motorcycle in the case of relatively large deformations. Bringing in extra measurement results and applying recent features of the MADYMO program can only improve the simulation results. It is believed that the motorcycle with rider model developed can provide better understanding of the collision mechanisms involved and predict trends as far as passive safety devices feasibility studies are concerned.

THE MOST CUSTOMARY APPROACH to performing motorcycle passive safety research is to carry out full scale crash tests involving a passenger car. This approach has two major disadvantages, one being the difficulty of reproducibility and the other being the fact that these tests are relatively costly and time consuming. The latter means that only a limited number of crash conditions can be addressed, whereas in reality motorcycles are subjected to a wide range of impacts. Regarding the disadvantages, it seems that computer simulations can contribute significantly to motorcycle passive safety research. The use of computer simulations has already been recognized as a powerful tool in the automotive passive safety field. Computer simulation of motorcycle rider behaviour during a crash, however, is far more difficult compared to the simulation of passenger car occupants, because of the more complex way in which motorcycles and their riders behave after impact.

In the past several simulation models have been developed. The earliest computer simulations of motorcycle impact were carried out at the Denver Research Institute between 1969 and 1979 under contract to NHTSA. A two-dimensional model was developed in which a simple rigid motorcycle, with three degrees of freedom, interacted with a slightly more complicated rider with seven degrees of freedom [1]*. In 1982 Sporner published a two-dimensional model for simulating a collision into the side-structure of a passenger car. In this model 8 segments linked together by joints were used to represent a 50th %ile Part 572 dummy. Contact interaction with the motorcycle was accounted for by means of 6 line segments. The kinematics of motorcycle as well as passenger car side-structure can be prescribed [3]. Also well known is the work carried out at Brunel University under contract to

* Numbers in parentheses designate references at the end of the paper

TRRL, which started as early as 1975. In 1987 the two-dimensional model representing motorcycle and rider shown in Figure 1 was presented [6]. Three years later a basic model was presented by TRRL for glancing impacts with a rigid barrier [10]. In 1991 the results were published of two studies involving an updated version of the ATB program. The first study concerns an evaluation of motorcycle leg protectors, in which three motorcycle types and 163 known impact conditions, based on the Los Angeles and Hannover accident databases, were considered. Prior to all these simulations, the models were validated on the basis of the results of full scale tests [13,15]. During the second study approximately 750 computer simulations were performed to assess the effects of a motorcycle airbag. No comparison with full scale data was made here [12]. Both studies were carried out by Dynamic Research Inc. The MATD-1 dummy applied consisted of 23 segments and the motorcycles were represented by 4 segments. Figure 2 illustrates both dummy and motorcycle geometry.

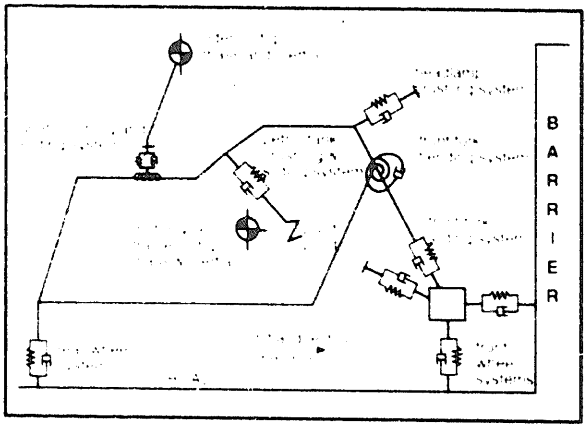

Fig. 1 Two-dimensional motorcycle with rider model after TRRL [6]

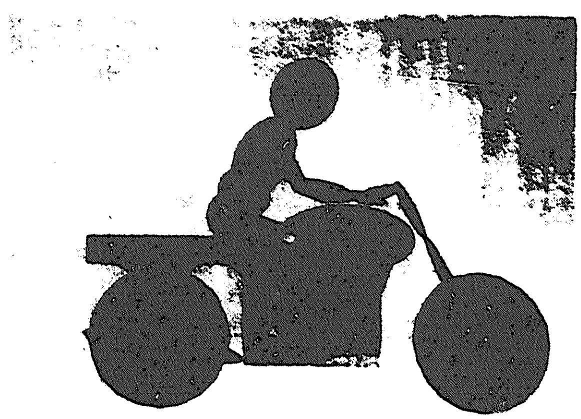

Fig. 2 Three-dimensional motorcycle with rider model, after DRI [13]

The work described here deals with the experimental and mathematical simulation of motorcycle crash behaviour and was conducted over a period of two years, starting in 1988. Several full scale motorcycle tests were carried out at the laboratories of the TNO Crash-Safety Research Centre, using a specially designed trolley for guiding the motorcycle and dummy prior to impact. The results of motorcycle to barrier tests and additional measurements, including measurements for determining inertia properties, were applied to establish a simulation model of the YAMAHA SRX-600 motorcycle. Version 4.2 of the MADYMO 3D program was applied for this purpose. MADYMO is a simulation program in world-wide use, specially designed for the study of the complex dynamic response of humans or human surrogates under extreme loading conditions [11]. The program has also been applied successfully for other dynamic events, such as the simulation of vehicle riding and handling [17] or the behaviour of a passenger car side-stucture under impact loading [16]. MADYMO combines multibody and finite element techniques with several force interaction models in one program.

Tests involving a motorcycle with rider and a passenger car were used to validate the motorcycle rider combination in a realistic crash environment. Both kinematics and time-histories were used for this validation, whereas in earlier work only acceleration peak levels were considered. The advantages and main shortcomings of the mathematical model will be discussed, as well as recent improvements made to the model, among which are a more detailed description of the collapse behaviour of the motorcycle front fork structure and a more accurate gastank geometry description. In conclusion, the potential of this kind of mathematical motorcycle model in the context of motorcycle passive safety device design will be discussed.

MOTORCYCLE MODEL INPUT DETERMINATION

The data required for developing a simulation model of the motorcycle were obtained from four different sources, i.e. geometrical measurements of the actual motorcycle, tests for determining spring and damper properties, inertia measurements and crash tests involving the motorcycle only into a load-cell barrier face. The latter crash test results were also applied for motorcycle model validation in an early stage.

The inertia measurements were carried out by the Technical University of Delft (TUD). During these measurements the gastank was filled with water. First the mass and the centre of gravity location of the complete motorcycle were measured. The motorcycle was then taken apart into the following segments: front wheel, front fork (including handle bar), main frame, rear suspension frame and rear wheel. Figure 3 shows the location and orientation of the segment coordinate systems. For each motorcycle segment, mass, centre of gravity (CG), moments of inertia about principal axes through the CG and orientation of the principal moments of inertia coordinate system relative to the segment coordinate system were determined. Chain and rear spring-damper elements were neglected in these measurements. For the front fork segment all properties were determined twice, once with a fixation of the front suspension taking the motorcycle weight into account and once taking a rider of 74 kg into account as well. The moments of inertia were measured by oscillating the motorcycle segment around a "knife-edge" (frictionless joint) for different segment positions. Figure 4 shows one position of the main frame segment. From the oscillation periods found, the moments of inertia about principal axes through the CG can be calculated. In addition to the inertia measurements, the spring and damping characteristics of the front suspension and the spring characteristics of the rear suspension were measured. An estimation of the tyre dry friction was obtained by pulling the motorcycle forward with blocked wheels by means of a load-cell.

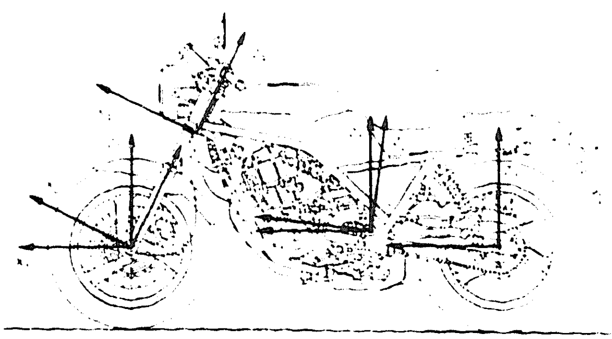

Fig. 3 Motorcycle segment coordinate systems

Motorcycle crash tests into a load-cell barrier were carried out to obtain dynamic input data on front fork and front wheel behaviour and to obtain test results for model validation. Three different test conditions were used, namely 90°/ 32.2 km/h, 90°/ 48.3 km/h and 67.5°/ 59.5 km/h, in which the angle represents the angle between the motorcycle's direction of travel and the load-cell barrier face. Three identical standard production type motorcycles were used for these tests. A special trolley was built to guide the motorcycle up to impact speed, see Figure 5. Standing in the trolley, the motorcycle is pushed forward at its rear axis and supported at the handlebar and the upper spring-damper element attachment points. A pneumatic lock connects the motorcycle to the trolley during the acceleration phase, in case an emergency stop is required. A signal conditioner can be placed on the trolley. During the actual tests the trolley was stopped approximately 5.5 meters in front of the load-cell barrier by means of crumple tubes. The motorcycle remained substantially upright during the last meters, while the deviation in impact location was less than 5 cm. The barrier was equipped with 36 load-cells, divided over 4 rows and 9 columns. The motorcycles were equipped with three triaxial accelerometers, one on each side of the motorcycle CG and one at the front fork, just above the front fender.

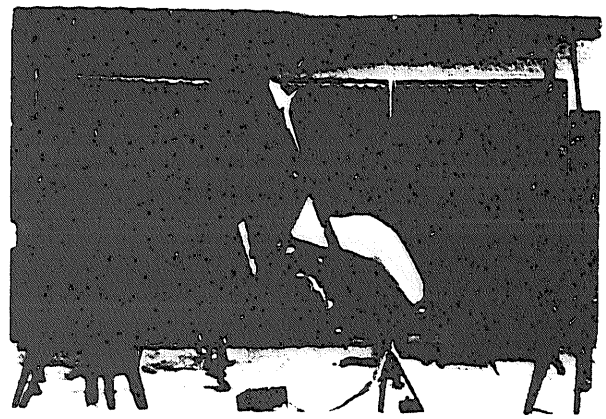

Fig. 4 Moments of inertia measurement set-up at the TUD

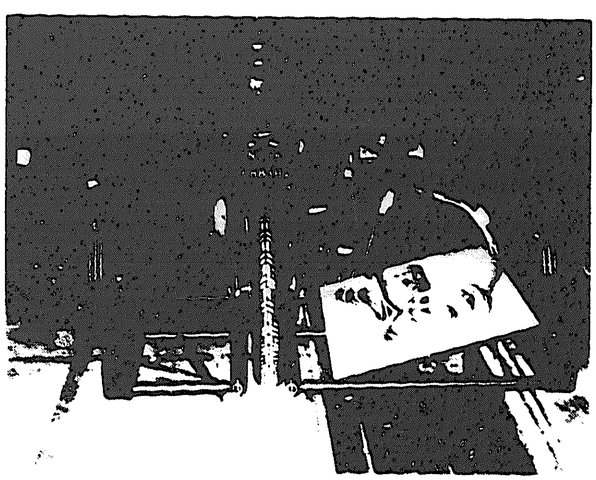

Fig. 5 Motorcycle trolley

During the 90° tests a certain amount of motorcycle pitch was observed. Figures 6, 7 and 8 show the motorcycle after the 90°/ 32.2 km/h, 90°/ 48.3 km/h and

67.5 / 59.5 km/h tests respectively. After the 32.2 km/h test only bending of the front fork was found. During the 48.3 km/h test the casted front wheel also broke. In the 59.5 km/h test, front fork bending as well as torsion was observed, the latter resulting in a broken damper house.

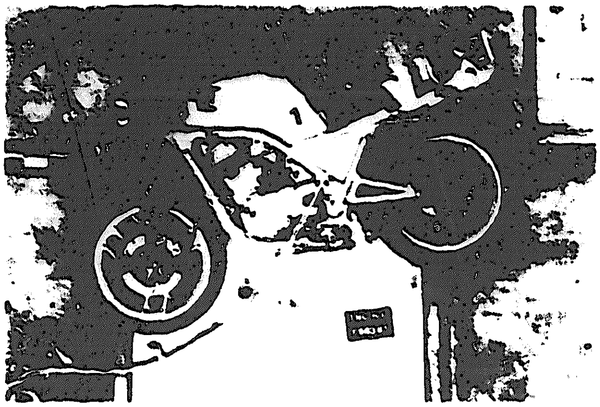

Fig. 6 Motorcycle after the 90° 32.2 km/h barrier test

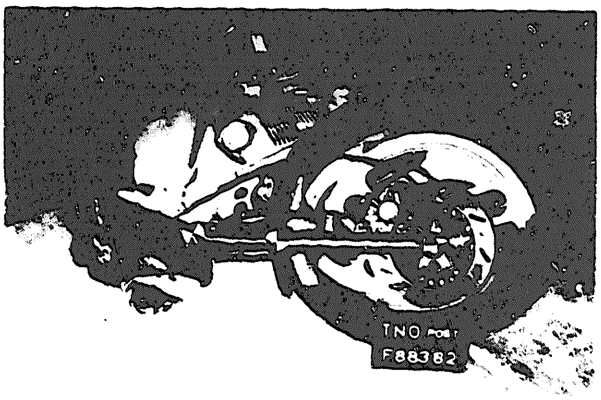

Fig. 7 Motorcycle after the 90° 48.3 km/h barrier test

Several target positions were digitized from high speed film (1000 fr/s). Together with information from the load-cell barrier, estimations could be made for bending and torsional stiffnesses of the front fork, tyre/wheel contact stiffness and headstock contact stiffness. Figure 9 shows the bending stiffnesses obtained from the 32.2 and 48.3 km/h barrier tests. As can be seen in this figure, an elastic fork deformation is followed by a plastic one, the second peak is introduced by the front wheel contacting the exhaust pipes/engine and is therefore not relevant for the front fork bending characteristic. In the 32.2 and 48.3 km/h tests this contact occurs after 22 and 15 ms respectively. Figure 10 shows the tyre/wheel contact stiffnesses obtained from the 32.2 and 48.3 km/h tests; it can be clearly seen that the front wheel broke during the 48.3 km/h test (vertical hysteresis slope). A top view of the 59.5 km/h test was used to determine the front fork torsional stiffness.

Fig. 8 Detail of motorcycle after the 67.5 59.5 km/h barrier test

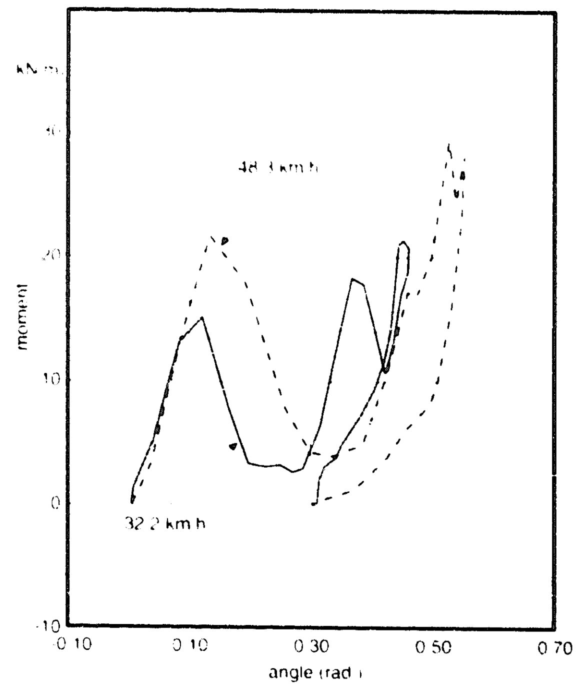

Fig. 9 Front fork bending stiffnesses

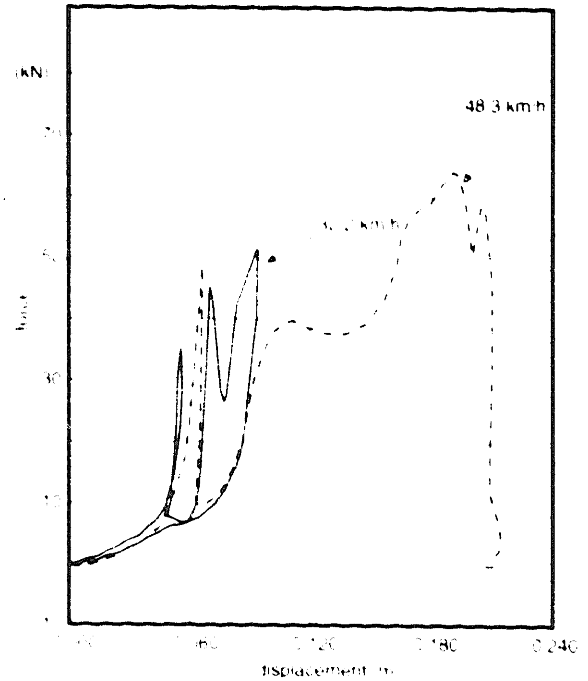

Fig. 10 Front tyre wheel contact stiffnesses

FULL SCALE CRASH TESTS

Two full scale crash tests were performed at the TNO Crash Safety Research Centre, in which the motorcycle with rider ran into a Mazda 323 passenger car. Figure 11 illustrates the impact conditions. The first involves a moving passenger car (32.2 km/h) and a moving (32.2 km/h) motorcycle with rider colliding into each other under an angle of 45. The second condition is a 90 impact with a stationary passenger car and a moving (48.3 km/h) motorcycle with rider. The first condition was tested twice, once as a so-called pre-test and once as the actual test. Results of the pre-test will not be discussed here. In order to support the dummy during the pre-release phase, the trolley was extended with a frame, see Figure 12. Until the trolley was stopped by crumple tubes, the dummy was prevented from sliding backwards by two supports, one at the height of the dummy pelvis and one at the height of the shoulders. In addition the neck bracket of the dummy was connected to a rail by means of a steel cable and a sliding mechanism, thus holding the dummy in the correct position, even for the short period after the motorcycle has left the trolley. The rider was represented by a 50th %ile Part 572 dummy with a pedestrian (standing) pelvis and pedestrian legs and feet. No helmet was applied. The instrumentation of the motorcycles was identical to the instrumentation used during the barrier tests. The dummy was equipped with 5 triaxial accelerometers, located in the head, chest, pelvis, left knee and right knee. Uniaxial accelerometers in the longitudinal direction were applied in the dummy's feet.

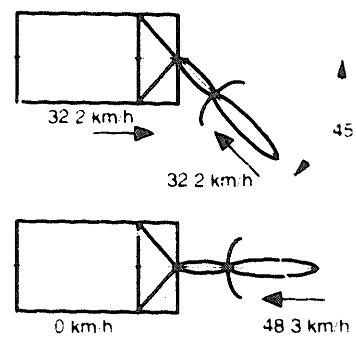

Fig. 11 Full scale crash test conditions

Figure 13 shows the situation after the 45 / 32.2 km/h / 32.2 km/h test. After 48 ms the left knee of the dummy contacted the right front fender of the passenger car, after approximately 97 ms the dummy's head contacted the hood. Figure 14 shows the situation after the 90 / 0 km/h / 48.3 km/h test. Both motorcycle and dummy showed a somersaulting motion, during this test. The motorcycle front fork was only slightly bent. The dummy's head contacted the hood only after approximately 160 ms.

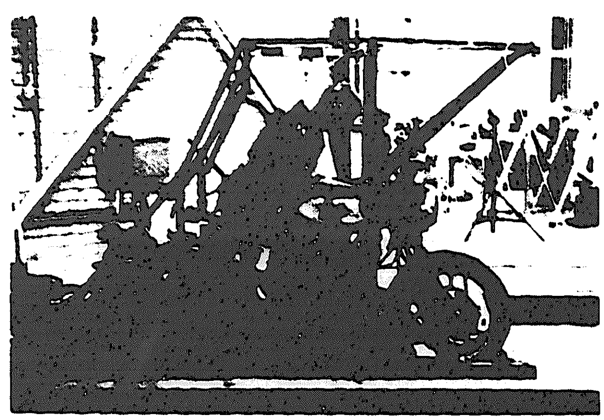

Fig. 12 Motorcycle trolley, including dummy support frame

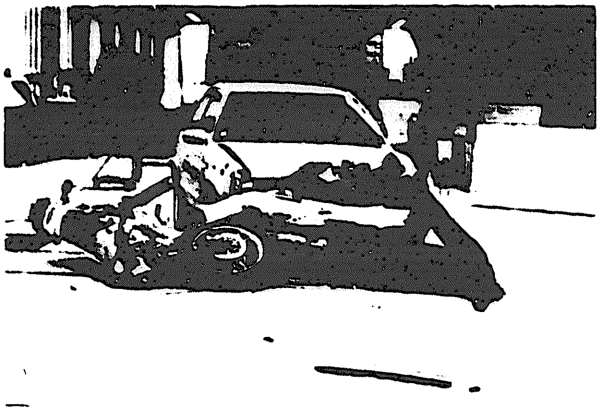

Fig. 13 Situation after the 45 / 32.2 km/h / 32.2 km/h test

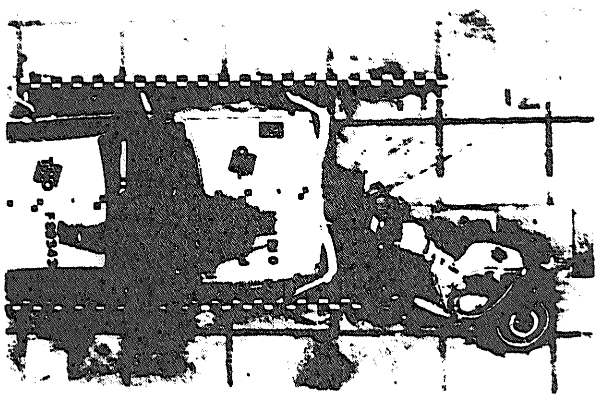

Fig. 14 Situation after the 90 / 0 km/h / 48.3 km/h test

MOTORCYCLE WITH RIDER MODEL DEVELOPMENT

The three-dimensional motorcycle with rider model was developed in two stages. The first stage involved the development and validation of the motorcycle model only. In the second stage this motorcycle model was adjusted to take rider interaction into account and the rider itself was incorporated. MADYMO version 4.2 was used for modelling.

The motorcycle model consists of 6 bodies, representing main frame, rear suspension, rear wheel, upper front fork, front wheel and lower front fork respectively. In combination with Kelvin elements separate rear wheel and rear suspension bodies allow proper rear suspension operation. A Kelvin element is a special spring-damper element in MADYMO, with non-linear damping properties [7]. The lower front fork body is connected to the upper part by means of four point-restraints [7], representing the front suspension stiffness and damping properties as well as its guiding mechanism. The motorcycle steering operation and the front fork bending properties are modelled in the same cardan joint. The torsion properties of the front fork are implemented in the joint for front wheel rotation. The stiffness for the front and rear wheel bodies is obtained from the 48.3 km/h curve in Figure 10, whereas the front fork bending characteristic initially is obtained from the 48.3 km/h curve in Figure 9 (first part of the curve, until the wheel contacts the engine). Figure 15 shows the initial motorcycle model set-up.

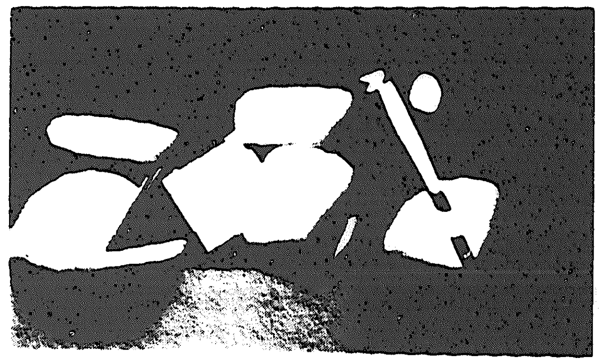

Fig. 15 Initial motorcycle model geometry

After an initial motorcycle model was developed, simulation and experimental results were compared for the three barrier test conditions. To be more precise, a comparison was made for: motorcycle kinematics (target locations after 50, 100 and 150 ms), motorcycle accelerations and contact forces between front wheel and load-cell barrier (only for the 32.2 km/h and 48.3 km/h tests). In addition permanent front fork bending and maximum inward stroke of the front suspension (only for the 32.2 km/h test) were compared. In the 59.5 km/h test the front wheel position was used for kinematics correlation purposes.

Figure 16 shows a side view of the kinematics, when simulating the 90 / 32.2 km/h test condition. The position of front and rear axis in the experiment is indicated by crosslets; the corresponding wheel contour is visualized by a dashed circle. The simulated permanent front fork bending is 0.28 rad; the permanent bending calculated from target positions before and after the test is 0.31 rad. These figures for the maximum inward stroke of the front suspension are 72.9 mm and 71.6 mm, the latter stroke being found from high speed film analyses. Figures 17 and 18 show a comparison between experimental and simulated signals for the resultant acceleration left of the motorcycle CG and the barrier load. In order to obtain these results, the 32.2 km/h fork bending curve in Figure 9 was applied in the model instead of the 48.3 km/h curve. However, the simulated kinematics for the 90 / 48.3 km/h test, as presented in Figure 19, will deteriorate as a result of introducing the "32.2 km/h characteristic". Part of the loading curve for front fork bending is probably deformation velocity dependent. This phenomenon could not be simulated effectively by version 4.2 of MADYMO. From Figure 19 it can be observed that the simulated pitch is too small. The main reason for this is the coupling between front fork bending and forward movement of the headstock. In order to eliminate this problem, an extra body and joint should be added to the motorcycle model. Figure 20 shows a top view of the simulated kinematics in the 67.5 / 59.5 km/h test; the crosslet indicates the foremost point of the front tyre in the experiment. The simulated acceleration signals look quite good, see Figures 21 and 22. However, in the experiment the motorcycle falls towards the barrier. Apparently the motorcycle contact with the barrier is too elastic; fortunately this falling to the wrong direction occurs in the rebound.

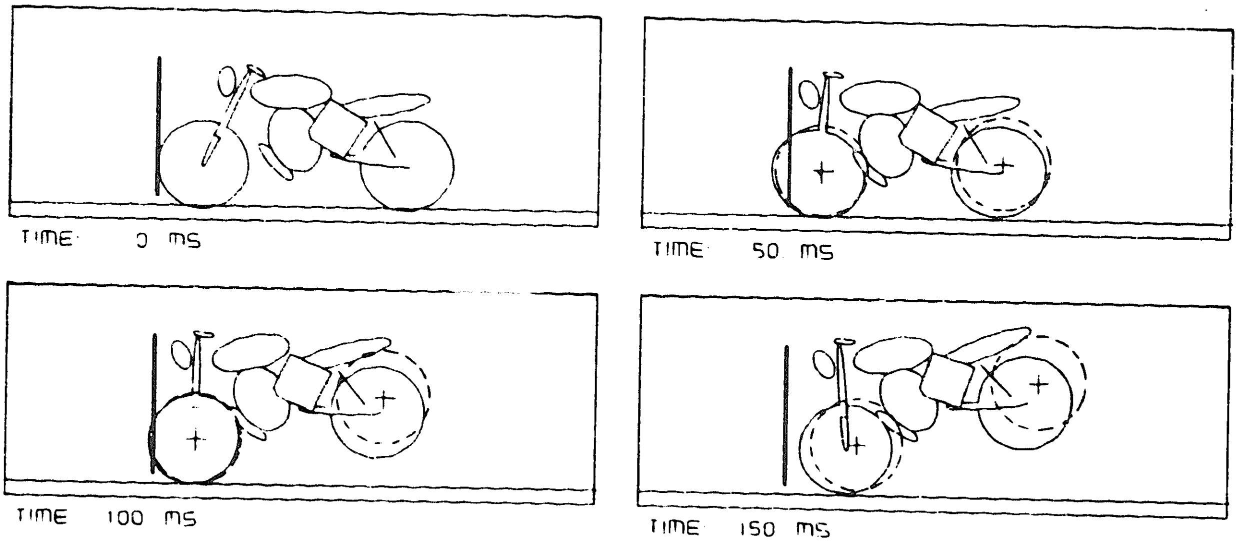

Fig 16 Simulated motorcycle kinematics for the 90 / 32.2 km/h barrier test condition

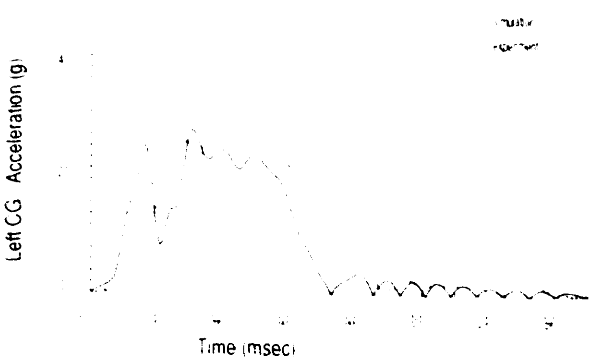

Fig. 17 Comparison between simulated and experimental resultant accelerations left of the CG for the 90 / 32.2 km/h test

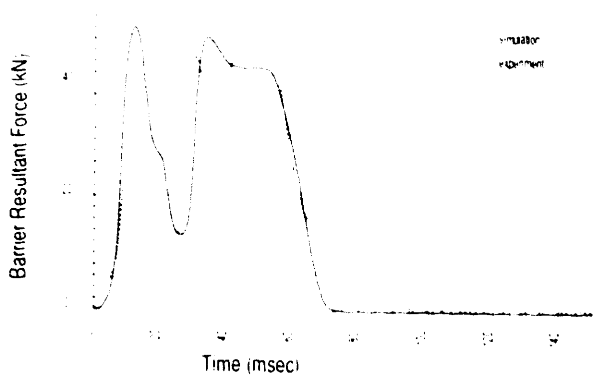

Fig. 18 Comparison between simulated and experimental barrier loads for the 90 / 32.2 km/h test

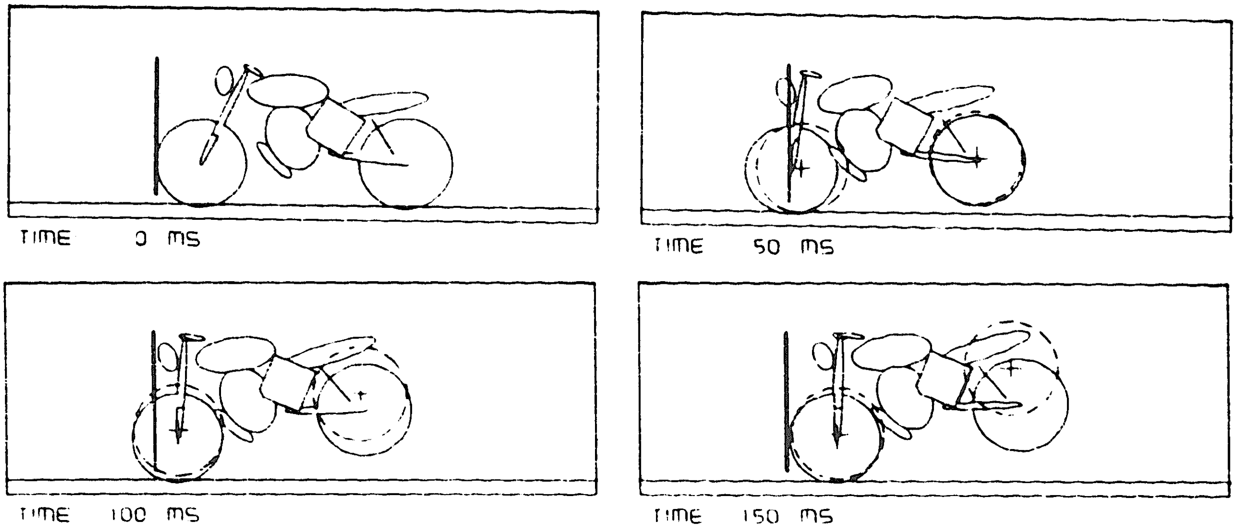

Fig 19 Simulated motorcycle kinematics for the 90 / 48.3 km/h barrier test

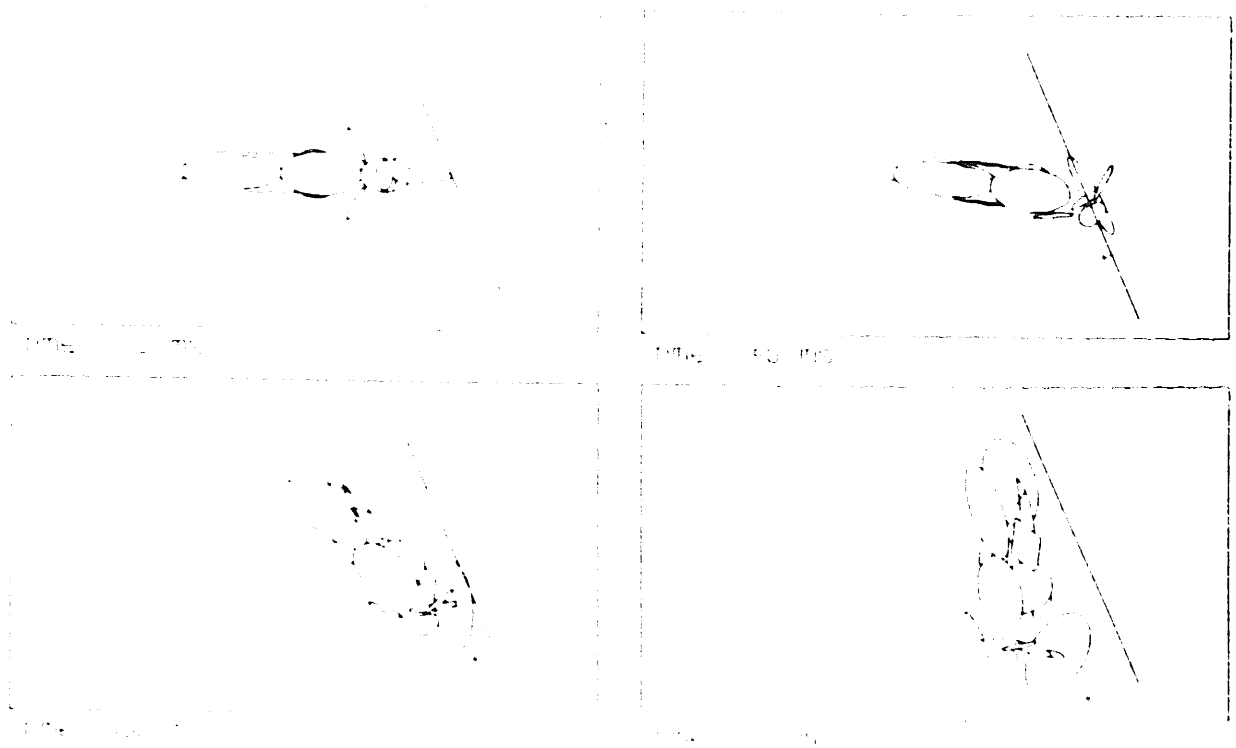

Fig 20 Simulated motorcycle kinematics for the 67.5 / 59.5 km/h barrier test

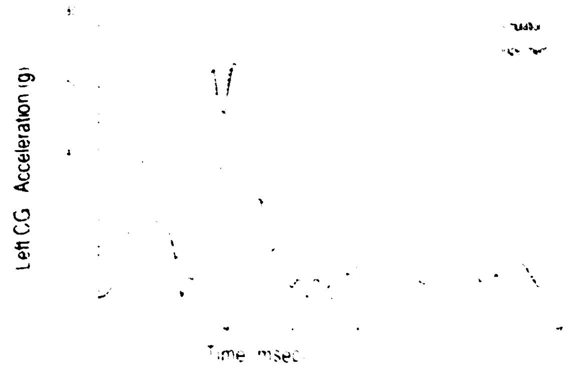

Fig. 21 Comparison between simulated and experimental resultant accelerations left of the CG for the 67.5 / 59.5 km/h test

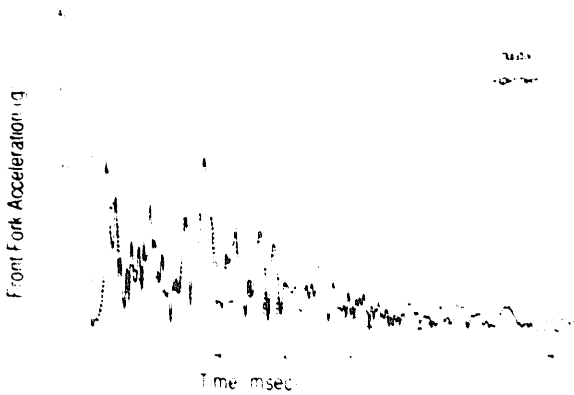

Fig. 22 Comparison between simulated and experimental resultant front fork accelerations for the 67.5 / 59.5 km/h test

In order to simulate the full scale motorcycle with rider tests into a passenger car, both a rider model and a model representing a Mazda 323 passenger car were required. In the experiments the rider was represented by a 50th %ile Part 572 dummy with a pedestrian pelvis and pedestrian legs and feet. Despite the construction differences, the deviation in mass distribution is small compared to a seated version of this dummy. In order to position the dummy properly on the motorcycle, separate hands and feet were introduced in the validated Part 572 dummy database in MADYMO [8]. Information for this purpose was obtained from literature [2,4] and an additional measurement to determine the flexion-extension and torsion properties for the dummy wrist. The location and orientation of the accelerometers in the dummy model are in accordance with the actual locations and orientations. Only the front of the passenger car is modelled in detail, using contact planes and ellipsoids to represent bumper, hood, windscreen, etc. The rest of the car is modelled by its inertia properties and four wheels which can rotate freely. When simulating the 90 / 0 km/h / 48.3 km/h test, car wheel rotation is obstructed by relatively stiff joint characteristics. The stiffnesses of car contact planes and ellipsoids were based on data in literature [5]. Note that the standard bumper stiffness is applied as specified.

In order to obtain a realistic interaction between dummy and motorcycle, some minor adjustments to the motorcycle model were necessary. For example, the gastank is represented by two fourth order ellipsoids instead of one and footrests were included. The dummy's initial position can be found from photographs taken prior to the test. The dummy's position just before impact, however, is slightly different. The upper body of the dummy lowers somewhat during the short time period in which contact is lost with the trolley. For this reason it was decided to position the dummy on the basis of target locations just before impact, digitized from high speed film. Due to the nature of motorcycle rider behaviour during a crash, a relatively large number of contact interactions had to be specified. To simulate the 45 / 32.2 km/h / 32.2 km/h and 90 / 0 km/h / 48.3 km/h tests, 46 and 36 contact interactions respectively were applied. For contacts between metal parts, a damping coefficient of 100 Ns/m was assumed. For all other contacts a damping coefficient of 1 Ns/m was specified. The friction coefficients used were either derived from measurements, tyre friction for example, or are empirical values.

MODEL VALIDATION IN A PASSENGER CAR COLLISION ENVIRONMENT

The full scale crash tests under the conditions 45 / 32.2 km/h / 32.2 km/h and 90 / 0 km/h / 48.3 km/h were simulated with the motorcycle with rider model developed. To compare simulated and experimental kinematics, several target and reference point positions after 50, 100 and 150 ms were digitized from high speed film. The dummy and motorcycle accelerations measured were also compared with the simulated accelerations.

Figure 23 shows a side view of the kinematics obtained from a simulation of the 45 / 32.2 km/h / 32.2 km/h condition. In this figure the crosslets indicate the location of motorcycle front wheel centre, motorcycle rear wheel centre, car left front wheel centre, dummy head, dummy pelvis and dummy's right knee during the experiment. Due to perspective in the film, the marked position of the car front wheel centre differs from the simulated centre. Figure 24 shows a top view of the same kinematics: the experimental positions of

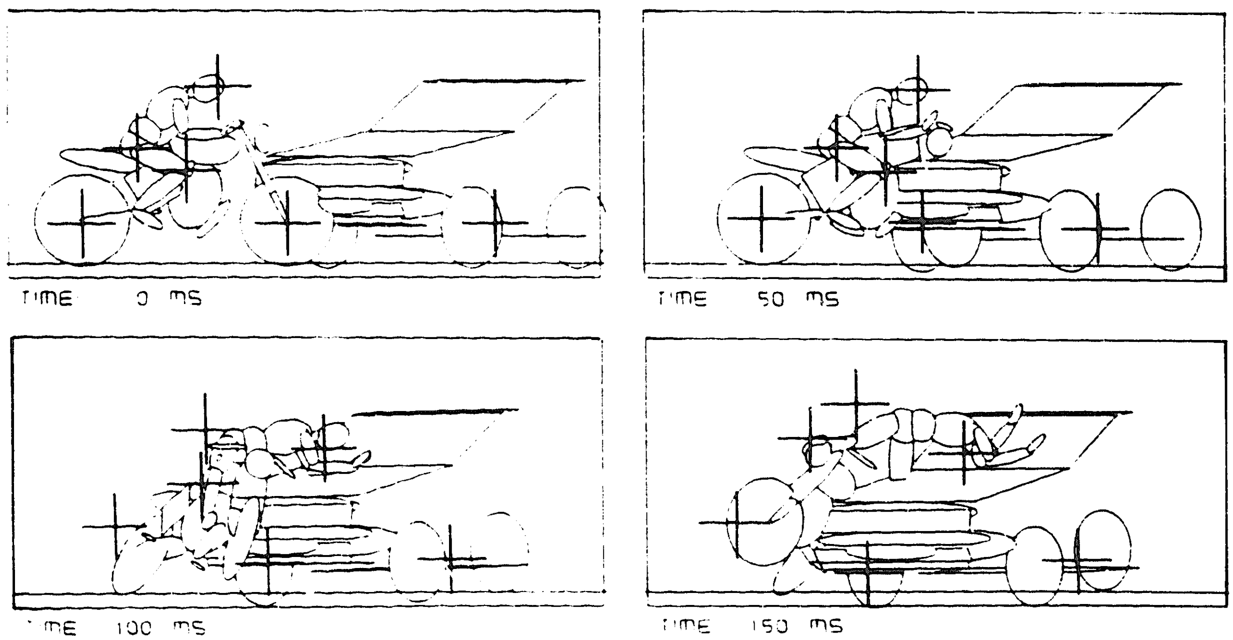

Fig. 23 Side view of simulated kinematics for the 45° / 32.2 km/h / 32.2 km/h test

front wheel "collision point", car target on hood, dummy head's back and motorcycle speedometer. In general it seems that the contact between passenger car and motorcycle front structure is too elastic. In reality, after 150 ms, the motorcycle just starts to detach itself from the car (see Figure 24) and the dummy head contacts the hood instead of the windscreen as simulated. The simulated acceleration signals do not correlate very well with experimental ones, except for the acceleration right of the motorcycle CG and the right knee acceleration. The peak accelerations simulated for the dummy are low compared to the measured peak values, moreover the timing is not always correct. The kinematics resulting from simulation of the 90 / 0 km/h / 48.3 km/h test are shown in Figure 25; crosslets are again included for comparison with the experiment. From this figure it can be learned that the kinematics are simulated reasonably well. A point of criticism could be the front wheel interaction with the passenger car. Note that this interaction is also affected by the way in which front fork bending is modelled. Looking at the simulated acceleration signals, one can conclude that the correlation, especially for the motorcycle accelerations, is slightly better compared to the correlation established for the 45°/ 32.2 km/h / 32.2 km/h test. Figure 26 illustrates a problem in the definition of the gastank shape. As can be seen in this figure, there is some discontinuity in the simulated signal due to the pelvis interaction with 2 independent hyperellipsoids. It is worth mentioning the fact that when simulating the 45°/ 32.2 km/h / 32.2 km/h test, the results are sensitive to the number of contact interactions between motorcycle and passenger car. For the 90° / 0 km/h / 48.3 km/h test condition, the stiffness and friction specified for the dummy interaction with the gastank was found to be important.

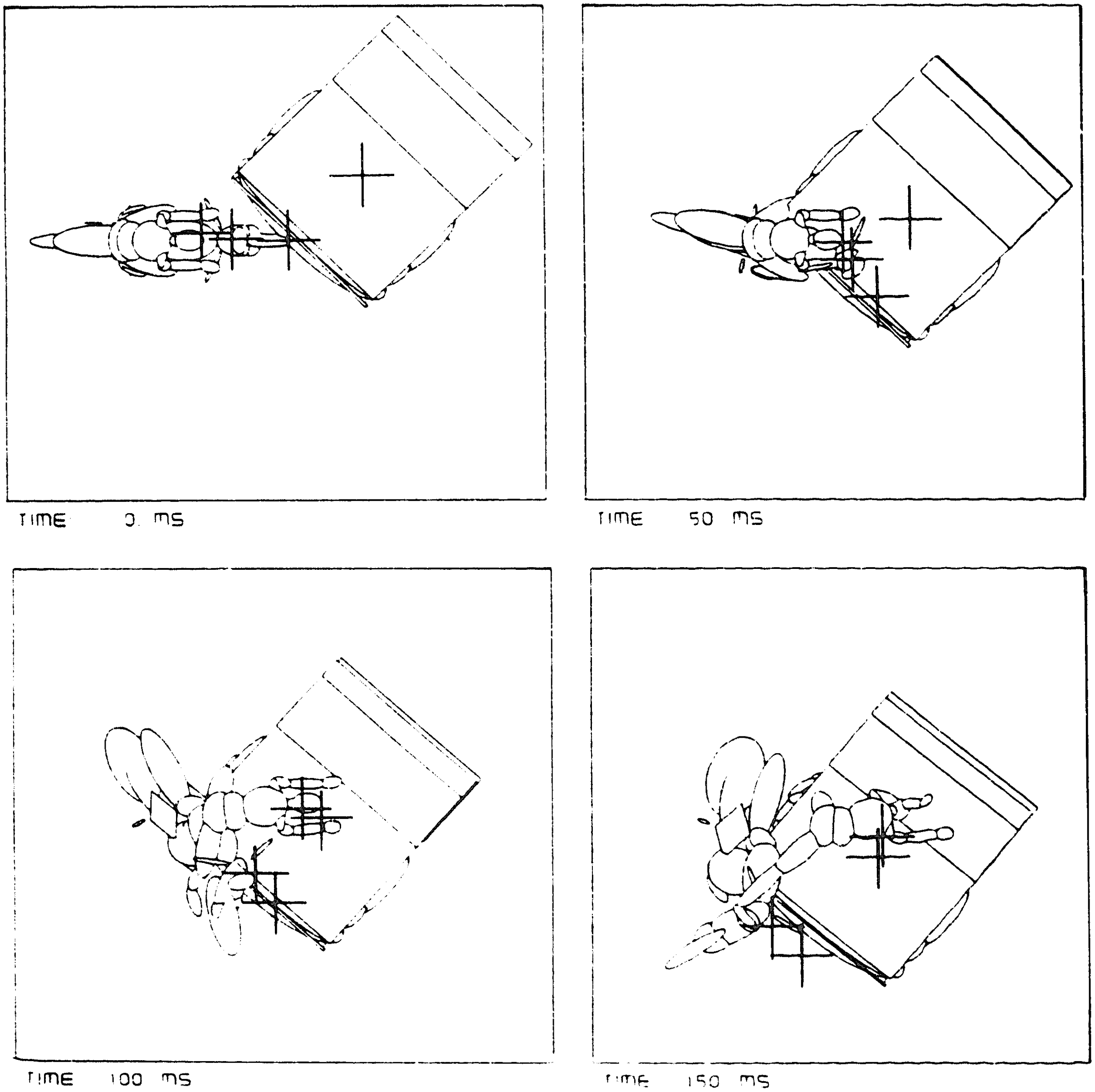

Fig. 24 Top view of simulated kinematics for the 45° / 32.2 km/h / 32.2 km/h test

PARAMETRIC STUDY

Based on the correlation established between simulated and experimental results so far and the drawbacks in the model discovered, it was decided to carry out a parametric study. Since the coupling between front fork bending and forward movement of the headstock seemed to be a problem, a more detailed front fork model was considered. Different gastank geometries and stiffnesses as well as dummy geometries were studied to assess the influence of these parameters on the rider kinematics. Furthermore, attention was paid to the front wheel model, as too elastic behaviour, especially for this part of the model, was experienced. Instead of presenting the results of each individual parameter change, the effect of a combination of parameter changes will be illustrated. Since the changes introduced were either based on measurements or realistic assumptions, the simulation results obtained give some idea about the accuracy of these kinds of complex simulation models.

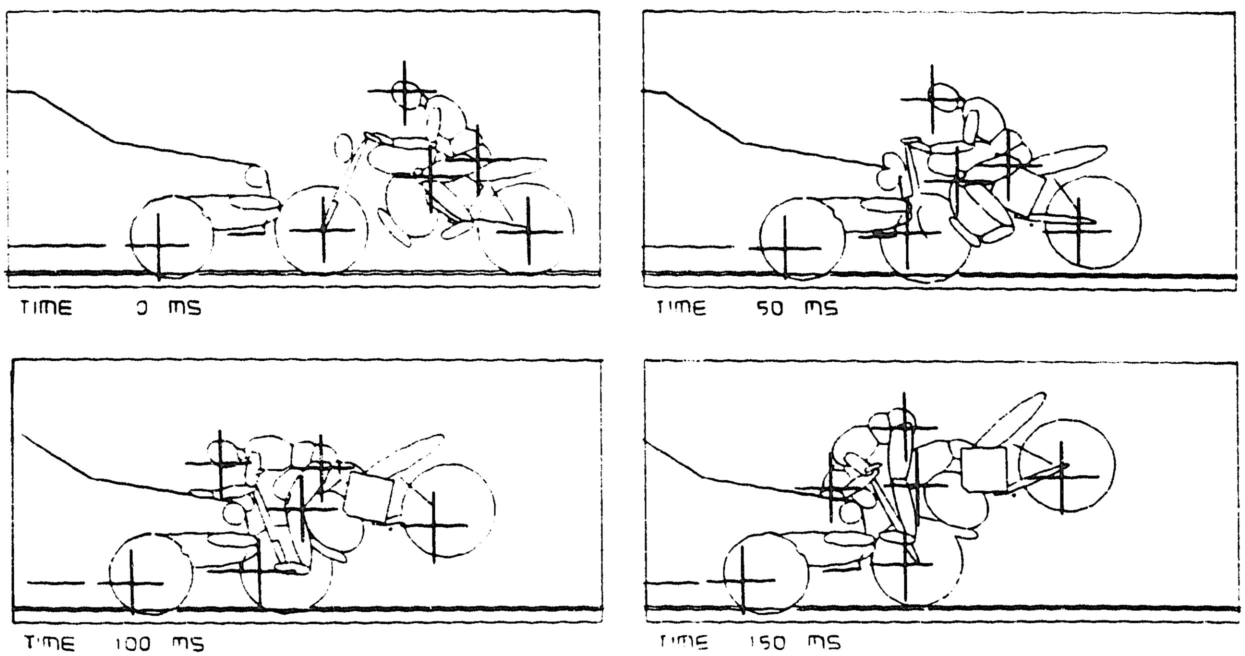

Fig. 25 Simulated kinematics for the 90 / 0 km/h / 48.3 km/h test

An extra joint and thus an extra body was introduced to represent more realistic front fork bending in the motorcycle model. It appeared that the "32.2 km/h bending characteristic" produced the most promising results, and was therefore used in the improved version of the model. Additional measurements were carried out to obtain the correct inertia properties for the new bodies. The gastank geometry as well as its stiffness were also adjusted, the resulting motorcycle model geometry is shown in Figure 27. The gastank stiffness was increased and "collapse behaviour" was added to the characteristic. The tyre/wheel characteristic is based on the 32.2 km/h curve of Figure 10. The spike in this curve at 0.055 m of deflection was omitted, since this spike is believed to originate from the bending behaviour of the front fork. The tyre/wheel contact stiffness was also reduced by 20 %, in order to take into account the passenger car bumper deformation.

As far as the rider model is concerned, it was proposed to include thumbs and heels by means of extra ellipsoids in order to ensure steady grip of hands and feet on handlebar and footrests. In addition flesh force-deflection characteristics were added for the dummy head, hands, chest, abdomen and femurs. The latter characteristics are based on measurements performed at JARI.

In order to simulate the 45 / 32.2 km/h / 32.2 km/h test it was found beneficial to have a more detailed front wheel model. A separate rim representation using two extra ellipsoids was chosen. Considering friction and damping coefficients, a parametric study indicated that the friction specified for initial contact points with the dummy (e.g. gastank, handlebar) has a relatively large influence on dummy behaviour. The damping in dummy contacts only has a small influence.

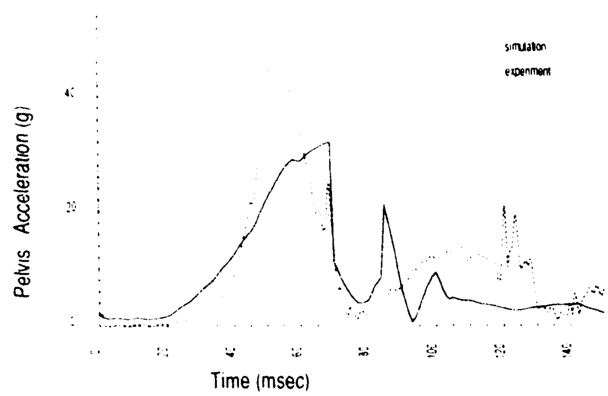

Fig. 26 Comparison between simulated and experimental resultant pelvis accelerations for the 90 / 0 km/h / 48.3 km/h test

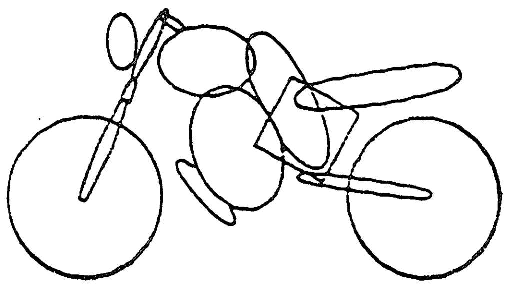

Fig 27 Adjusted motorcycle model geometry

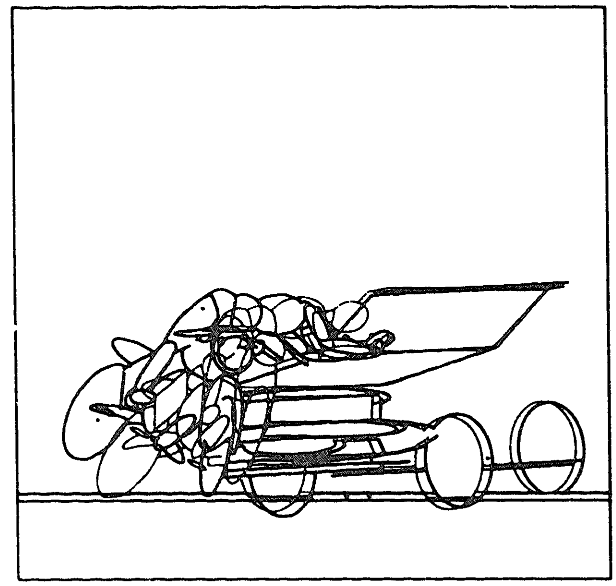

Fig. 28 Simulated kinematics for the 45 / 32.2 km/h / 32.2 km/h test with and without parameter changes

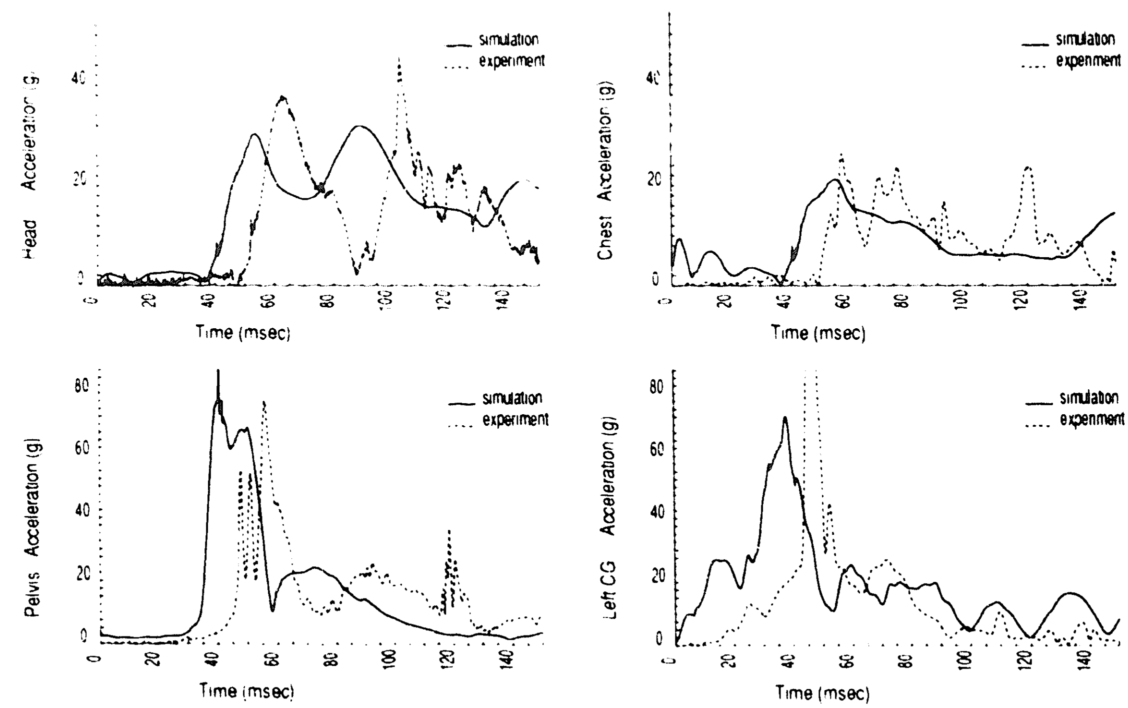

Fig. 29 Comparison between simulated and experimental resultant accelerations for the 45 / 32.2 km/h / 32.2 km/h test using the improved model.

Figure 28 shows the simulated kinematics of the 45 / 32.2 km/h / 32.2 km/h test after 100 ms, before (thin line) and after (thick line) the parameter changes described above were implemented. As can be seen from the figure, the dummy kinematics have greatly improved, for example the head now hits the hood correctly and the position of the motorcycle rear wheel is also more realistic. However, the interaction between motorcycle front structure and passenger car is still too elastic. In Figure 29 a comparison is made between experimental resultant accelerations and those simulated with the improved model for the 45 / 32.2 km/h / 32.2 km/h configuration. A comparison is included for the head, chest and pelvis accelerations, as well as for the motorcycle acceleration left of the CG. A reasonable correlation can be observed. One can imagine the difficulty of including the right contacts to obtain the right acceleration peak at the right point in time for these kinds of simulations. Figure 30 shows the improved kinematics (thick line) after 100 ms for 90 / 0 km/h / 48.3 km/h test simulation. The more realistic front fork bending is clearly illustrated in this figure. Finally, Figure 31 illustrates the comparison between experimental and simulated resultant acceleration signals for test condition 90 / 0 km/h / 48.3 km/h. All acceleration signals have improved: as an example the resultant pelvis acceleration in this figure can be compared with the one shown in Figure 26.

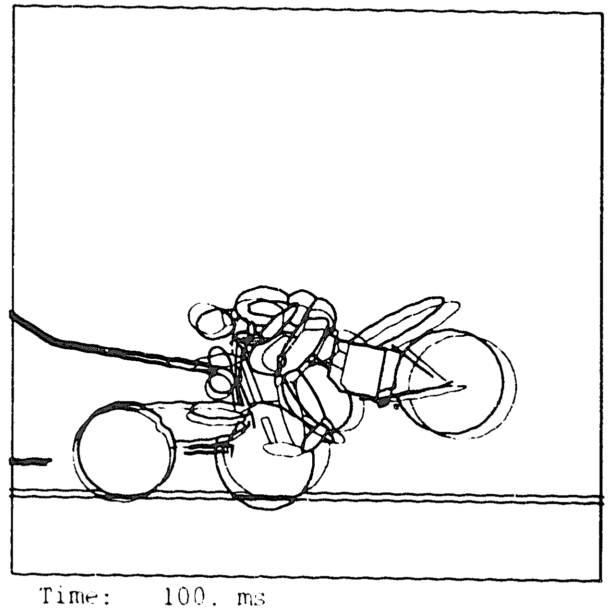

Fig. 30 Simulated kinematics for the 90 / 0 km/h / 48.3 km/h test with and without parameter changes

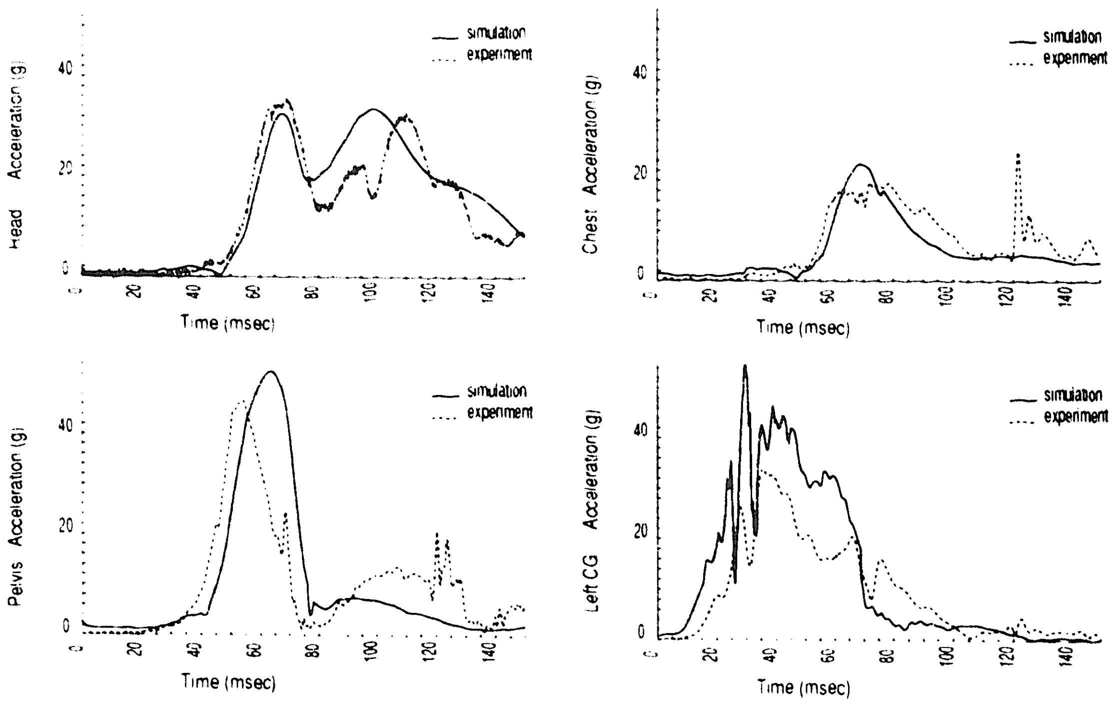

Fig. 31 Comparison between simulated and experimental resultant accelerations for the 90 / 0 km/h / 48.3 km/h test using the improved model

DISCUSSION

In this study an advanced three-dimensional mathematical model of a motorcycle was developed. In a second stage the motorcycle model was extended with a rider and passenger car model to assess its performance in real life crash situations. Both the model input determination process and the validation strategy are explained in this paper.

Computer simulation of motorcycle rider behaviour during a collision event is far more difficult than the simulation of passenger car occupants. This is due to the complex way in which motorcycles and their riders behave after impact and the numerous contact interactions required in a mathematical model associated with this. The occupants in a passenger car interact, in a predictive way, only with the car interior during a crash. This is particularly true if they are well restrained. The motorcycle rider interacts with the motorcycle, the motorcycle interacts with the passenger car (or another collision partner), but the rider interacts with the car directly as well. Considering these complex contact interactions, a step-by-step approach to specify more complete mechanical properties for each model component is often needed to improve the accuracy of simulation. Future research will deal with aspects of major interest, such as the gastank, the front fork and the front wheel. As far as the gastank is concerned, force-deflection properties of different types could be determined. As a result of the parameter study described, it was necessary to include a separate joint for bending in the front fork model. Although usable dynamic stiffness information was obtained from high speed film analyses combined with barrier loads, it is planned to measure the front fork bending stiffness in a more simple and repeatable manner, statically as well as dynamically at different velocities. Another area of research is the accurate measurement of wheel stiffnesses, in particular the effect of the orientation of the cast wheels (hit a spoke or not) prior to impact.

The simulation results obtained are very promising; even time-histories of dummy and motorcycle accelerations show an acceptable correlation. These kind of motorcycle with rider models provide a better understanding of the collision mechanisms involved and predict trends (even before the first prototype has been built) as far as design changes are concerned. As a result, a more overall evaluation is feasible in view of design improvement in passive safety. For example, this approach has started to be used to evaluate safety devices such as motorcycle leg protectors [13] or airbag systems [9,12,14,18]. The main drawback of the motorcycle model as it is presented in this paper is the fact that the energy absorption is underestimated for relatively large structural deformations. The current version 5.0 of MADYMO offers adequate features to improve the description of this phenomenon. For example damping can now be specified as a function of velocity or (penetration dependent) elastic contact force. Moreover, a dynamic amplification factor can be defined for contact interactions as well as joint characteristics. Version 5.0 of MADYMO offers kinematic joints, among which revolute and translational joints [19]. Application of these joints in the motorcycle model, for example to represent the front suspension, results in an even more efficient model.

One should always be aware of the complexity of a motorcycle crash environment. Simulation models as presented here are only trend predictive within certain limits. With regard to the present study, this means that in order to simulate a head-on impact at 80 km/h or an impact into the side-structure of a moving passenger car, additional validation and possibly modelling activities have to be carried out. When aiming at a consistent model for simulating a wide range of real world impacts, many more contact interactions and consequently force-deflection properties should be defined. It is believed that computer simulation of motorcycle and rider response during a crash is an important research activity, from which motorcycle riders involved in a collision event can directly benefit.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Technical University of Delft for performing the inertia measurements on the YAMAHA SRX-600 motorcycle.

REFERENCES

1. R.E. Knight and H. Peterson - Dynamics of Motorcycle Impact, Volume II: Digital Computer Simulation of Two-Dimensional Motion of Motorcycle and Dummy Rider; Final Report DOT-HS-800-588, 1971.

2. R.P. Hubbard and D.G. McLeod - Geometric, Inertial, and Joint Characteristics of Two Part 572 Dummies for Occupant Modelling ; SAE 770937, 21th Stapp Car Crash Conference, New Orleans, October 19-21, 1977.

3. A. Sporner - Experimentelle und Mathematische Simulation von Motorradkollisionen im Vergleich zum realen Unfallgeschehen; Dissertation, Technischen Universität München, Mai, 1982.

4. J.T. Fleck, F.E. Butler and N.J. DeLeys - Validation of the Crash Victim Simulator, Volume 2, Engineering Manual, Part II: Validation Effort; Calspan Corporation, August, 1982.

5. S. Backaitis, S. Daniel, D. Cesari and C. Cavallero - Comparison of Pedestrian Kinematics and Injuries in Staged Impact Tests with Cadavers and Mathematical 2D Simulations; SAE 830186, International Congress and Exposition, Detroit, February 28-March 4, 1983.

6. J. Happian-Smith, M.A. Macaulay and B.P. Chinn - Motorcycle Impact Simulation and Practical Verification; 11th International Technical Conference on Experimental Safety Vehicles, Washington D.C., May 12-15, 1987.

7. MADYMO User's Manual 3D, Version 4.2; TNO Road-Vehicles Research Institute, October, 1988.

8. MADYMO Databases Manual, Version 4.2; TNO Road-Vehicles Research Institute, October, 1988.

9. J. Happian-Smith and B.P. Chinn - Simulation of Airbag Restraint Systems in Forward Impacts of Motorcycles; SAE 900752, International Congress and Exposition, Detroit, February 26-March 2, 1990.

10. J. Happian-Smith, M.A. Macaulay and B.P. Chinn - Computer Simulation of a Simple Motorcycle in Glancing Impacts with a Rigid Barrier; SAE 900754, International Congress and Exposition, Detroit, February 26-March 2, 1990.

11. H.A. Lupker, P.J.A. de Coo, J.J. Nieboer and J. Wismans - Advances in MADYMO Crash Simulations; SAE 910879, International Congress and Exposition, Detroit, February 25-March 1, 1991.

12. N.M. Rogers - A Preliminary Study Into the Feasibility of Motorcycle Airbags; Safety Environment Future, Proceedings of the 1991 International Motorcycle Conference, Bochum, 1991.

13. J.W. Zellner, S.A. Kebschull and K.D. Wiley - Motorcycle Leg Protectors: An Analysis of Overall Effectiveness Via Computer Simulation; Safety Environment Future, Proceedings of the 1991 International Motorcycle Conference, Bochum, 1991.

14. J.J. Nieboer, A.P. Goudswaard and J. Wismans - Computer Simulation of Motorcycle Airbag Systems; 13th International Technical Conference on Experimental Safety Vehicles, Paris, November 4-7, 1991.

15. N.M. Rogers - A Technical Evaluation of Motorcycle Leg Protectors; 13th International Conference on Experimental Safety Vehicles, Paris, November 4-7, 1991.

16. P.J.A. de Coo, E.G. Janssen, A.P. Goudswaard and J. Wismans - Simulation Model for Vehicle Performance Improvement in Lateral Collisions; 13th International Technical Conference on Experimental Safety Vehicles, Paris, November 4-7, 1991.

17. H.A. Lupker and W.P. Koppens - MADYMO Vehicle Dynamics Application; Proceedings 3rd International MADYMO Users' Meeting, Detroit, February 27-28, 1992.

18. J. Wismans, A.P. Goudswaard and J.J. Nieboer - Motorcycle Airbag Systems; Bag & Belt '92, 2nd International Akzo Symposium on Occupant Restraint Systems, Cologne, March 25-27, 1992.

19. MADYMO User's Manual 3D, Version 5.0; TNO Road-Vehicles Research Institute, July, 1992.