

Validation of Sled Tests for Far-Side Occupant Kinematics Using MADYMO

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ABSTRACT

Far-side occupants are not addressed in current government regulations around the world even though they account for up to 40% of occupant HARM in side impact crashes. Consequently, there are very few crash tests with far-side dummies available to researchers. Sled tests are frequently used to replicate the dynamic conditions of a full-scale crash test in a controlled setting. However, in far-side crashes the complexity of the occupant kinematics is increased by the longer duration of the motion and by the increased rotation of the vehicle. The successful duplication of occupant motion in these crashes confirms that a sled test is an effective, cost-efficient means of testing and developing far-side occupant restraints or injury countermeasures.

Previous work by these authors analyzed 9 crash modes that represent 44% of the total far-side occupant crash exposure and account for 56% of all MAIS3+ far-side injured occupants in the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS). The study developed a methodology for using MADYMO to specify the sled test conditions that mimic a far-side occupant's kinematics for a wide range of crash environments, including cases with significant vehicle rotation. The approach used both crash tests and finite element models (FEM) to determine the crash pulse. The dummy motion was determined by MADYMO simulations [1].

Another technique was developed by Smyth and Smith in which they used a pulse from a full-scale crash test to develop a pulse shape, pulse magnitude, and Principle Direction of Force (PDOF) for a sled test [2]. The kinematics of the dummies in the resulting sled test was generally similar

to the dummy kinematics in the crash test. Similarly, the study found that sled tests can be used to simulate highly complicated crashes in which the crash pulse was established by a crash test.

The purpose of this study is to validate the previously developed MADYMO methodology using the crash pulse and dummy kinematics from the actual crash and sled tests presented by Smyth and Smith. Furthermore, a comparison of each technique is analyzed in MADYMO and the results are discussed to determine how each may be best applied for future research and testing of far-side countermeasures.

INTRODUCTION

Far-side occupants are defined as occupants seated on the non-struck side of a vehicle and as such experience a significantly different crash environment than occupants seated on the struck, or near-side of the vehicle. Various factors contribute to this difference including restraint design and the relative motion of the occupant within the vehicle during an accident. This leads to the theory that far-side injury mechanisms are different from that of near-side injury mechanisms and require different countermeasures than those currently in place for near-side occupants [3].

Another important consideration is that near-side occupants contact the inside of the vehicle within 50 ms of the initial impact while far-side occupants can strike the interior as late as 180 ms after impact [4]. This is particularly significant in side collisions since near-side passengers are commonly hit by the intruding interior while far-side occupants have sufficient interior space to permit more of the crash energy to be absorbed by restraint systems before contact with the vehicle interior occurs. Far-side occupants are involved in

50% of side crashes and account for up to 40% of occupant HARM [5]. However, no current government research and regulations are aimed at protecting the occupants seated on the non-struck side of the vehicle [3].

This lack of research led to the formation of an international group of universities and crashworthiness research groups that began investigating the problem of far-side crashes in 2004 [3]. The three main objectives of the group were to 1) gain a detailed understanding of far-side crashes, injuries, and injury mechanisms, 2) develop suitable test procedures, and 3) identify far-side injury countermeasures to address the trauma [6]. Previous research has analyzed the crash environments that produce injuries in far-side impacts [3, 7]. A large number of crashes that produce serious injuries occur in impacts that result in rotation of the subject vehicle. The far-side injury countermeasures currently being evaluated in sled tests do not consider the affect of the vehicle rotation [8]. For this reason there exists a need for sled tests that allow far-side countermeasures to be developed economically.

The present study is based on previous works by the authors that have developed a methodology of running sled tests that replicate the crash environment of an impact with significant vehicle rotation [1, 2]. In 2007, Smyth and Smith established a process to derive the PDOF, pulse shape, and pulse magnitude of a sled pulse from actual crash test data. The procedure considered cases with both negligible yaw rates, such as the Federal Motor Vehicle Safety Standard (FMVSS) 208 frontal barrier test, and high yaw rates, such as a high speed corner impact [2]. The study validated the methodology by running a vehicle-to-vehicle crash test and then prepared a sled test using those results. The occupants' head motions were tracked in both tests and results were presented that confirmed occupant kinematics. These results demonstrated that a sled test can be used to accurately model an occupant's motion in crashes with high yaw rates [2].

In 2008, Cuadrado developed a similar methodology specifically intended to mimic the motion of far-side occupants in a high yaw impact through the use of MADYMO (MATHematical DYnamic MOdels). For the purpose of this paper this methodology will be referred to as the 'simulation methodology.' A review of the National Highway Traffic Safety Administration (NHTSA) database showed that as of 2007 there were over 5000 crash tests, but only three tests were found to have been performed with a far-side dummy. These tests were unable to be used in the research because they were not instrumented with accelerometers in the lateral direction and poor video quality prevented accurate yaw data from being obtained through video analysis. Since no government tests could be analyzed, the kinematics of far-side occupants exposed to corner impacts is largely unknown. For this reason far-side occupant motion first needed to be determined in order to design a sled test for each considered case. MADYMO was chosen as an

easy and cost effective means of testing and analyzing far-side occupant motion in the study. In total, 9 tests were chosen based on five full-scale crash tests and four finite element simulations that matched the PDOF and impact locations identified in a NASS/CDS corner impact query. The research successfully developed a methodology to design a sled test model that replicates the motion of a far-side occupant involved in a variety of side impacts, corner impacts, and a narrow-object frontal offset impact. Since the models were not based on the motion of an actual far-side occupant, the models were unable to be validated against the kinematics of an actual far-side dummy. The purpose of this paper is to validate the methodology developed by Cuadrado using the crash test and sled tests presented by Smyth and Smith. Additionally, the methodology developed by Smyth and Smith will be modeled in MADYMO in order to compare the two techniques.

NASS/CDS ANALYSIS

In 2008, Cuadrado studied the National Automotive Sampling System/Crashworthiness Data System (NASS/CDS) data to analyze the crash population distribution and to determine the percentage of the crashes represented by the nine cases modeled in the research. The analysis considered all NASS/CDS cases between 1997 and 2005 and initially filtered the total crash population by the 'General Area of Damage' (GAD), as specified in the Collision Deformation Classification (CDC), SAE J244 recommended practice. NASS/CDS showed that over 84% of automotive crashes are to the front or side of the crash-involved vehicles. Two additional variables specified by the CDC are the 'Principle Direction of Force' (PDOF) and 'Specific Longitudinal Location (SHL1), which specifies the location of the damage along the front, rear, or side of the vehicle. In Figure 1 the numbers are the PDOF clock direction and the letters are the SHL1 damage locations. The front and side GAD cases were filtered to only include occupants age 16 or older involved in planar crashes with the PDOF and bold area of damage locations (SHL1) shown in the figure below. The conditions were chosen to represent the crash modes that were expected to cause vehicle rotation and were studied in the analysis of far-side occupant motion. Although frontal impacts account for 57% of the total crash population, only 6% of the cases met the PDOF and damage location requirements for the study, but 38% of all side impacts met the damage requirements.

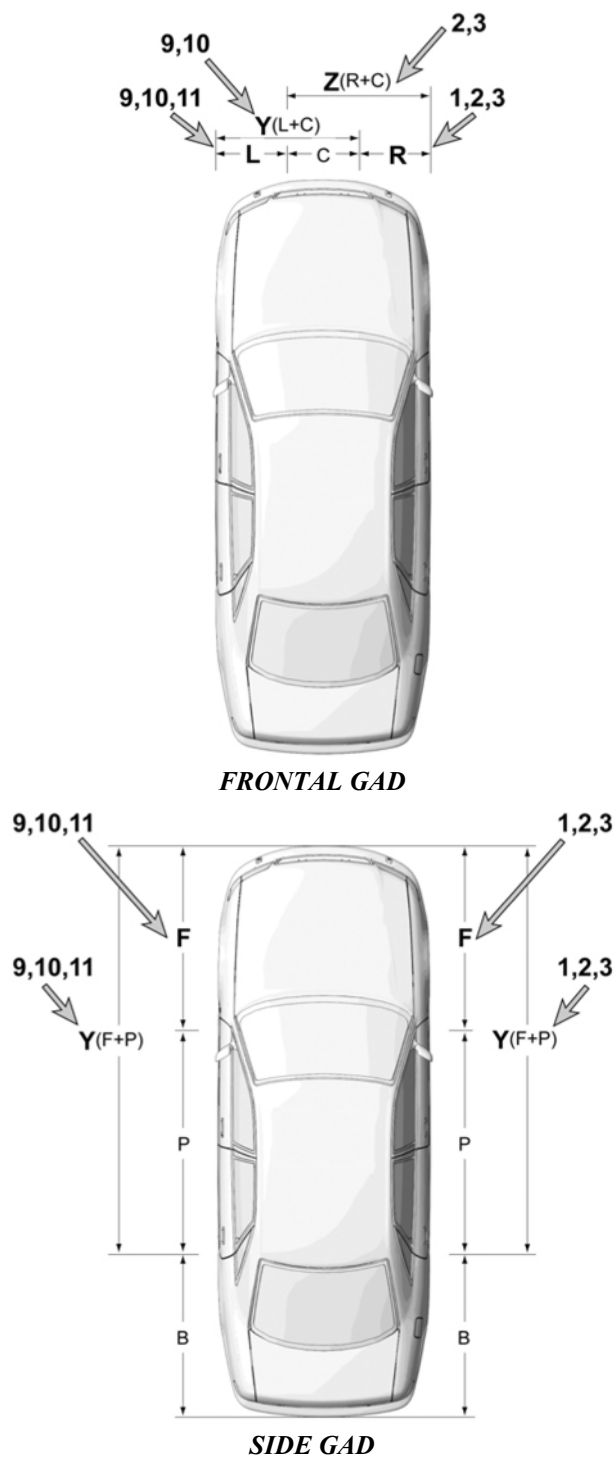


Figure 1. Analyzed Corner Impact PDOF and Damage Location Conditions

The research defined a ‘far-side impact’ as drivers exposed to the PDOF 1, 2, and 3 o’clock conditions shown above or passengers exposed to the PDOF 9, 10, and 11 o’clock conditions shown above. Additionally filtering the data to far-side cases shows that 6.6% of all occupants involved in an automotive crash, or approximately 144,000 occupants each

year, are seated on the non-struck side of the vehicle and exposed to these corner far-side crash modes. Comparing the total number of corner impact cases to the total number of far-side cases showed that 47% of occupants are seated on the non-struck side of the vehicle and the remaining 53% are seated on the struck side. Similar results were presented in a side impact analysis of the NASS/CDS database where 49% of side cases were far-side and 51% were near-side [3].

<table 1 here>

It was observed that approximately 78% of the cases involved impacts to the passenger side of the vehicle. Considering the previous observation that the right and left side of the vehicle are struck at approximately the same rate, the distribution difference in far-side cases is a result of a passenger not always being present in a vehicle. For this reason a near-side impact for a passenger will always register as a far-side impact for the driver, but a near-side impact of a driver requires the presence of a passenger in order to be registered as a far-side impact. This statistic is also similar to the Gabler study which found that 76% of far-side cases were to the passenger side of the vehicle.

The SHL1 distribution of all side impact cases with a far-side occupant present was analyzed to further compare the results with that of the Gabler study (Table 2). The ‘F’ and ‘Y’ SHL1 locations were also considered in this study and are presented in parenthesis below the Gabler figures. The difference between the two numbers is due to the PDOF restrictions present in this study, whereas Gabler analyzed all cases for a given SHL1 [3].

<table 2 here>

The data in Table 2 reveals that 42% of all far-side occupants exposed to side impacts occur to the ‘Y’ or ‘F’ SHL1 locations and account for 53% of the MAIS3+ side impacts. These crashes make up the side corner impact population that analyzed in the study. An additional 507,707 frontal corner impacts were also analyzed in the study and would represent 16% of the previously studied data. These additional frontal corner impacts have not been considered in any previous far-side study. By considering the total far-side population, 44.3% (1,877,328 of 4,233,370 impacts) of all far-side cases were represented by the 9 crash modes in the study.

METHODOLOGY

VECTOR ANALYSIS METHODOLOGY

In 2007, Smyth and Smith presented a process to derive the PDOF and sled pulse from actual crash test data. The procedure considered cases with negligible yaw rates, such as the Federal Motor Vehicle Safety Standard (FMVSS) 208

frontal barrier test, and high yaw rates, such as a high speed corner impact [2].

For events with low yaw rates, the crash test PDOF was determined using accelerometer data and calculating the instantaneous PDOF throughout the event. The sled test PDOF was determined by averaging the crash test PDOF over a wide time interval. Although the instantaneous PDOF contains high-frequency variability, it remains relatively constant throughout the event. Therefore, the exact time interval over which the average is taken is of little importance so long as the interval is large enough. For events with high yaw rates the crash pulse and PDOF is different for each occupant [9]. Since a sled test cannot simulate the rotating vehicle, data must be processed at an occupant location of interest. The instantaneous PDOF for this location can be determined using accelerometer data; however, since the PDOF changes throughout the event, an average must be chosen over a short time interval. Choosing this interval can prove difficult since the average PDOF can vary widely with small changes in the choice of time interval. Averaging the PDOF can be misleading since this method also weights periods with low accelerations the same as those with high accelerations. Periods with low accelerations have little effect on the velocity at the location of interest, and ultimately that velocity is of most interest. The limitations of using instantaneous PDOF were overcome by presenting a method in which the velocity vectors were used to calculate PDOF. Since velocity is calculated by integrating the accelerations with respect to time, this method takes into account the time-history of acceleration and appropriately accounts for both its magnitude and duration. Using this method, a 'critical time' must be chosen and then the PDOF at that instant can be calculated. This critical time is defined by the moment when the occupant significantly impacts the vehicle interior. The sled test PDOF angle is then determined from this result and adjusted for the vehicle yaw angle at the critical time.

Two techniques were presented to calculate the sled pulse. It should be noted that once the accelerations were calculated at the seating position of interest, the method for determining the sled pulse was the same for events with both low and high yaw rates. The first technique involved calculating the resultant acceleration and then scaling that result so that it matched the delta-V at the critical time. This method provided a good representation of both the pulse shape, and the delta-V up to and including the critical time. An alternate approach was also presented wherein the pulse was determined from differentiating the velocity. This method yielded an approach that matched the delta-V throughout the entire time frame, and did not require scaling.

The methodology was illustrated by conducting a crash test with high yaw rates and then comparing occupant motion to a sled test that was set up for the left rear occupant. This position was chosen because it was a far-side occupant and

any error would have been exacerbated by the long distance the ATD traveled before contacting the vehicle interior. Head contact with the front seatback was shown to correlate well between the two tests. Video analysis was used to track the ATD's head motion during both tests, and the results were used to demonstrate that the dummy's head path was curved for the crash test and generally straight for the sled test. This was due primarily to the fact that the camera was located on the rotating vehicle reference frame, as opposed to effects from interaction with the restraint. This analysis highlighted the fact that the time when occupants impact the vehicle interior, or the critical time, may be needed to determine the appropriate PDOF of a sled test. Choosing a critical time becomes most important for those impacts with very high yaw rates, and especially for far-side occupants, where unimpeded travel distances are at their highest.

SIMULATION METHODOLOGY

Crash tests and finite element models were used to obtain the crash pulse experienced by a far-side occupant involved in side impacts, corner impacts, and a narrow frontal offset crash. The pulse and yaw were used to model the event and capture the far-side occupant motion through the use of MADYMO simulations. Sled tests were developed to replicate the occupant motion up to the critical time, when the occupant significantly impacted the vehicle interior. The sled pulse was modeled as a sine function with a delta-V equivalent to the actual crash test. The sled buck was initially rotated to the impact angle of the crash test, and the instrument panel was rotated to the position where it was located at the critical time of the crash test simulation. The sled angle and pulse were then varied until the kinematics and injury response of the occupant in the sled test mimicked that of the occupant in the crash test.

During this study, only one vehicle geometry was used to model each pulse so that the effect of the sled angle could be isolated from the occupant motion. This simplification also allowed for a baseline comparison between crash tests by eliminating differences due to different vehicle interior geometries. The NHTSA/NHTSA National Crash Analysis Center's vehicle modeling laboratory has created a library of vehicle finite element models that are available for download and public use. At that time the database contained 3 sedan models, the most detailed of which was a 2001 Ford Taurus. This model was chosen for the MADYMO simulations because 4 of the 5 actual crash tests were performed with sedans. In order to minimize the time to compile each simulation, the Taurus model was reduced to only components that would be interacting with the occupant during the tests. The model was simplified further by using larger elements to capture the interior geometry of the vehicle (Figure 2). For all simulations, the occupant was positioned in the front passenger seating position. Although more far-side accidents occur with an occupant in the driver seating

position, the passenger position was chosen to allow for a greater travel distance before interacting with the vehicle instrument panel.

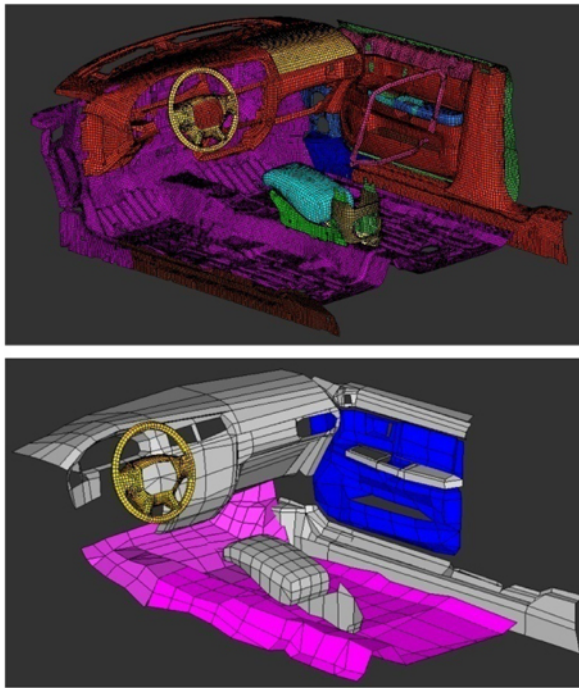


Figure 2. Taurus Cabin: Original Finite Element Model (top) and simplified model (bottom)

Only the frames of the seats were modeled in the original Taurus finite element model. For this reason, the seating position of the dummy model was imported from the 2000 Ford Taurus SNCAP NHTSA Test Report 3263. Once the dummy was properly positioned, the seat was then modeled underneath the dummy. This technique takes into account any seat cushion deflection that occurs as a result of the dummy's weight.

The x-, y-, and z-acceleration data and yaw angle experienced by the subject vehicle in each crash test and finite element model were used to create the acceleration environment for the MADYMO model, and also used to determine the motion that a far-side occupant would undergo in each crash mode. MADYMO was chosen for these simulations because it was originally designed to study occupant kinematics in automotive crashes. The human faceted model was chosen for the occupant because its validity in far-side impacts has been demonstrated [10]. The far-side occupant motion was then compared with the response of a sled test model that was also run in MADYMO. Parameters of the sled test model, such as the sled pulse and PDOF, were altered until the occupant contacted the vehicle interior in the same location and at the same time as that of the crash pulse model.

Both the Haversine function, Eq. (1), and Sine function, Eq. (2), were considered in the analysis. These functions were chosen because they are relatively simple in nature and can be duplicated by nearly all sled test facilities. The accuracy of the results presented in the research should only increase with an increase in the complexity of the sled pulse [2]. Due to the frequent use of delta-V in the field of automotive safety and in accident investigations, the pulses were defined in terms of delta-v and pulse duration [11].

$$a_{Haversine} = \frac{2 \cdot \Delta V}{T} \cdot \sin^2 \left(\frac{\pi \cdot t}{T} \right) \quad (1)$$

$$a_{Sine} = \frac{\Delta V \cdot \pi}{2T} \cdot \sin \left(\frac{\pi \cdot t}{T} \right) \quad (2)$$

The reference condition for the evaluation of occupant motion was with the occupant restrained by only a lap belt. The lap belt configuration was chosen to maximize the amount of distance the occupant's head would travel unimpeded. Errors that may be indistinguishable when comparing 3-point belted occupants were exacerbated due to the longer travel distance. The proper configuration was then simulated and compared with occupants using 3-point restraints. The final sled test configuration can then be used in an actual sled test to mimic the motion of a far-side occupant that is exposed to the original crash environment.

Results from initial sled test simulations revealed that the angle between the occupant's torso and the instrument panel differed significantly between the crash pulse model and sled test model (Figure 3). The difference is evident only in models where vehicle yaw is a factor.

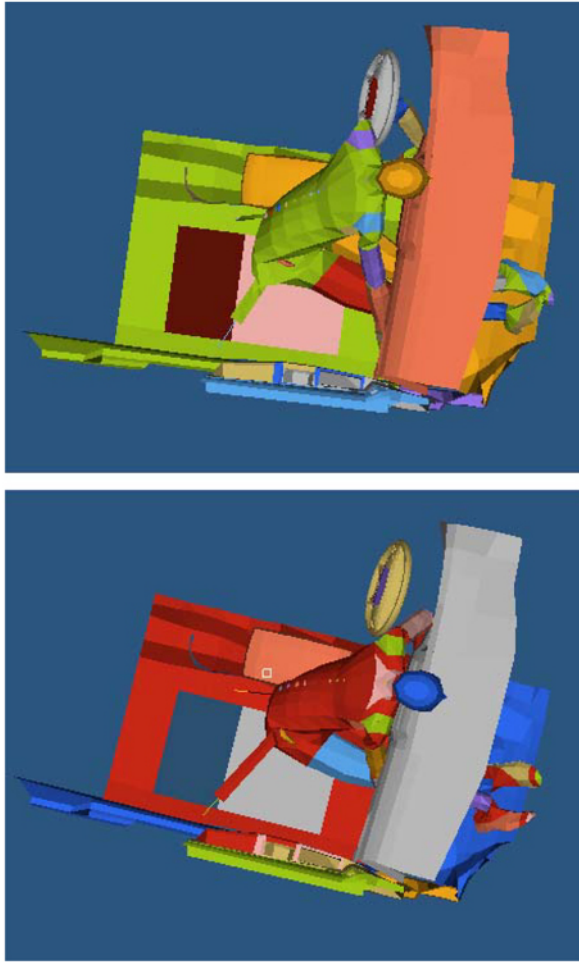


Figure 3. Comparison of 30° Corner Impact Crash Pulse Model (top) to Initial Sled Test (bottom)

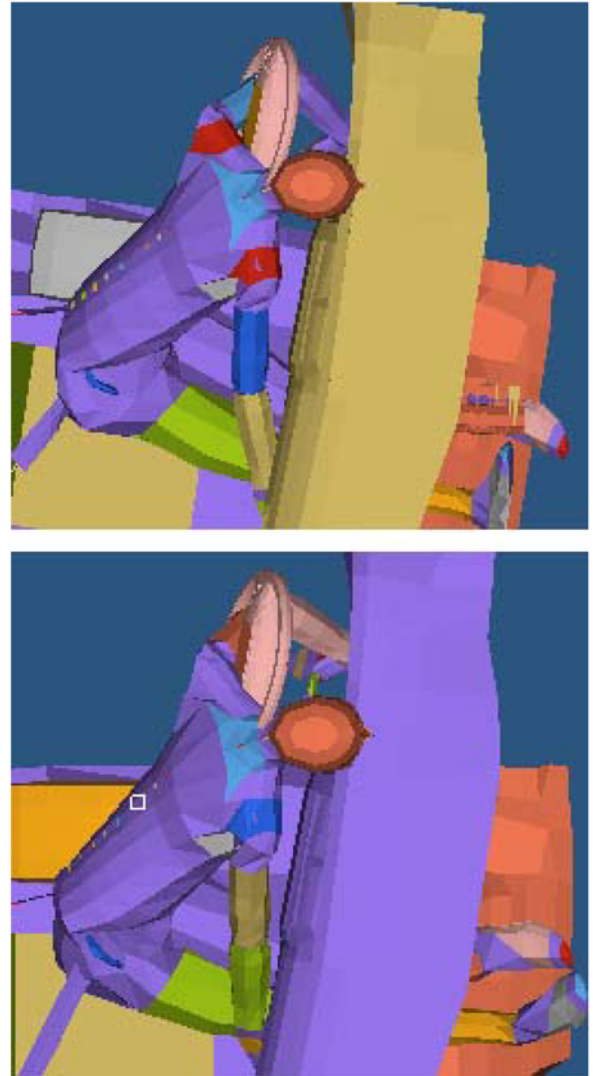


Figure 4. Comparison of 30° Corner Impact Crash Pulse Model (top) to Sled Test with Rotated Instrument Panel (bottom)

This methodology was enhanced by considering the yaw angle of the instrument panel at the critical time. Since the contact time and center of gravity were known for each crash test model in which yaw was significant, this information was used to rotate the instrument panel about the vehicle center of gravity, and position it at the appropriate angle during the time when the occupant contacted the instrument panel. As can be seen in [Figure 4](#), this technique allowed for vehicle rotation to be considered, thus giving a more accurate comparison of the occupant motion with respect to contact with the instrument panel. From this point forward, the occupant motion was compared in the local coordinate system of the rotated instrument panel using the RELATIVE_BODY_POS card in MADYMO ([Figure 5](#)).

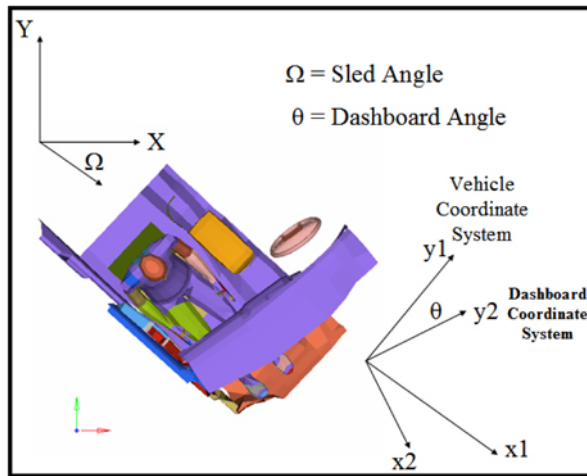


Figure 5. Coordinate Systems of Sled Test Models with Rotated Instrument Panel

CURRENT RESEARCH METHODOLOGY

The simulated sled test methodology developed by Cuadrado was validated against crash test models in MADYMO, but the crash test models have not been validated versus actual far-side kinematics due to a lack of far-side test data. The purpose of this research is to validate this methodology in its entirety by comparing the results with the crash and sled tests presented by Smyth and Smith. The dummies in the crash test and sled test were not instrumented; however, a hole was cut in the roof of each vehicle so that video tracking could be used to determine the occupant's head paths. For the purpose of this study, the driver was chosen as the occupant of interest since it was wearing a three point restraint and the left rear occupant was wearing only a lap belt. The head path information was utilized to validate simulation parameters such as restraint performance. Once the crash test model is validated, a sled test model will be setup using the parameters of the actual sled test, and results will be compared to further validate the approach. Note that the sled test was set up for the left rear occupant, so driver kinematics of this simulation can be compared only to that of the actual sled test and not to the actual crash test.

In order to validate the crash test and sled test simulations, several modifications were made to the vehicle model used in the Cuadrado research. The previous model only contained the passenger side of the occupant compartment because at the time that was the seating position of interest. In this study the occupant of interest is the driver, so the floorboard and door were mirrored such that the geometry of both the passenger's and the driver's side of the occupant compartment was included. The front seats in the Smyth crash test and sled test experienced significant deformation as a result of the rear ATDs impacting the seat and the overload of the right seat

track during the sled test. For this reason, the seat was video-tracked up to the critical time to include this motion in the models. The seat was also a bench seat, as opposed to a bucket seat in the previous research, so the seat geometry was modified to represent the actual geometry present in the subject tests. Seat belt webbing loads were not recorded during the actual tests so the load characteristics were unknown. As a result, the load characteristics of the seat belts in the MADYMO application database were used. Analysis of the high speed video and comparison with initial simulation results showed that there was approximately 3.5 inches of webbing travel at the D-ring prior to significant webbing load. This estimate is slightly larger than the 2.2 inches of webbing spool recorded in a 1984 Chevrolet Celebrity seat belt in NHTSA Test No. CE0105, but it is realistic for belts of that type and generation. Consideration of this movement was incorporated into the final restraint model.

Validation of the simulations of both the crash test and the sled test were conducted by comparing the driver's head paths with the known paths obtained from high-speed video analysis of the actual testing. Once these models were validated, the methodologies previously developed by these authors were applied to the crash test at the driver position and modeled in MADYMO. Each technique used a 'critical time' in order to determine the sled parameters. For the simulation of the Smyth and Smith methodology, the left front pulse was developed using differentiated velocity data at the left front seating position. The sled angle was determined using vector analysis of the velocities at the critical time.

For the Cuadrado methodology, the instrument panel was rotated about the vehicle's center of gravity to the vehicle's yaw angle at the critical time. This results in the appropriate angle of incidence between the head velocity vector and the vehicle's steering wheel. The initial pulse and PDOF for the sled simulation were chosen based on the Smyth and Smith methodology, and then the parameters were varied until the occupant kinematics matched that of the crash test simulation. These variations are generally small and can be explained, at least in part, by the fact that each point in a rotating vehicle experiences a different pulse and PDOF. In other words, the restraint mounts move differently than the center of the occupant's seat, which is itself different than the contact point on the steering wheel. Only one point can be chosen for an actual sled test, and that point was the center of the occupant's seat. Note that in the previous research the reference condition was a computer simulation of an occupant restrained with only a lap belt, and in the present research the reference condition is an actual crash test with a dummy wearing a 3-point restraint.

The following MADYMO simulations will be employed: