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Advancing Racing Safety: An Overview

C. D. Foster, P. C. Begeman, and J. W. Melvin

ABSTRACT

Efforts to improve the safety of a driver of a racecar that is involved in a crash have been ongoing for a number of years. The Wayne State University Bioengineering Center has examined issues related to motorsports injury for over a decade. The Center has tested polypropylene tubes, automotive tires, foam and other non-rigid materials configured in various patterns as energy absorbing barriers. Presently, the Bioengineering Center is participating in development of the SAFER (Steel And Foam Energy Reducing) barrier for racetrack outer walls by providing biomechanical analysis of crash dummy data from crash tests conducted by the University of Nebraska–Lincoln Midwest Roadside Safety Facility. Associated with this effort is the examination of head and neck restraints such as the HANS (Head And Neck Support) device, seats with integrated headrests, and head net arrangements.

Due to the high speeds attained during racing and the highly restrained nature of the driver, racecar drivers are at particular risk to an injury known as basilar skull fracture. The risk of basilar skull fracture is increased as the neck axial tension force approaches 4100 N. This makes the axial tension load in the neck a critical measurement of safety device performance. The performance of head and neck restraints in crash sled tests using a Hybrid III 50th percentile dummy and a NASCAR style buck subjected to a 50 g crash pulse over a duration of 60 msec was evaluated. It was found that a driver not fitted with a head and neck restraint could experience a neck axial tension of 4900 N. However, it was shown that with a HANS device the neck axial forces were kept below 1500 N. Furthermore, tests using actual racecars that were pulled into barriers showed that the HANS along with other technologies provided a level of safety that previously was unavailable. By keeping HIC below 700 and the neck tension below 4100N, the HANS device along with the SAFER barrier, and a proper head rest with a well positioned head net, have been shown to be effective in racecar crash tests at 150 mph and an angle of 20 degrees.

This paper provides an overview of some of the more significant motorsports activities in which the Bioengineering Center is involved. Testing conducted during the development of the SAFER barrier is described. Included is a discussion of head and neck restraint system evaluation efforts.

INTRODUCTION

The improvement of automobile racing safety has been an ongoing research and development effort. Recently, Wayne State University (WSU) teamed up with a number of organizations to evaluate and develop technologies for use in the sport of automobile racing. These technologies either act on the driver directly such as seats or harnesses, or they attempt to control the crash energies developed by vehicle to barrier contact. The goal is to minimize the likelihood of a driver suffering a serious injury as a result of a crash.

In 1992 General Motors (GM) created the General Motors Motorsports Safety Technology Research Program (GMMSTRP). The goal of the program was to apply crash protection research methods for passenger vehicles to racing vehicles. The emphasis was on measuring the crash forces acting on the driver (Melvin et al., 2001). While GM was in the field collecting race crash data, WSU was back in the lab testing the technologies in use at that time to start a baseline of knowledge.

Beginning with testing of tire-wall barriers in 1994, WSU and the GMMSTRP have conducted well over 200 tests of various safety devices. This program was eventually transferred to WSU fully after the GMMSTRP dissolved, and now GM Racing is the sponsor for motorsports safety testing at WSU. To this date WSU and GM Racing continue the effort to keep the safety of racing advancing.

This document highlights several areas of interest on which WSU has focused on in the last 10 years. The earliest testing involved evaluation of tire-wall barriers already in use, and examined some proposed configurations. Demonstration of stockcar seat performance during lateral impacts helped manufacturers improve the design of those seats. A later effort was the evaluation of head and neck restraints, which were intended to control neck tension forces and head whipping motions that occur during race crashes. The latest and most recent area of interest is the development of trackside barrier systems such as the Steel And Foam Energy Reduction (SAFER) barrier.

Tires stacked as walls and barriers have been in use at tracksides for a long time (Metz, 2002). For example, the Portland and Laguna raceways each have used stacked tires as barriers. Each track had its own method of stacking the tires and attaching them together to form a barrier. Some were stacked as if they were bricks in a wall, while others were merely cylinders of tires bound together. Each configuration had its merits and detractions.

According to John Pierce, then of General Motors, the force deflection characteristics of stacked tires and tire walls was not well known, and the development of trackside barriers would require understanding a tire stack's ability to reduce crash energies. This would mean comparing stacked tire configurations to each other, and to modifications of existing stacking methods.

Early seat design for stockcar racing had very little to do with safety, and was more concerned with weight reduction. These seats were constructed of thin gage aluminum, had headrests shoulder supports attached to them that could support the driver’s head and shoulder during cornering, but provided very little resistance during impact. Initial tests were conducted with unmodified seats to show how well the seats controlled the driver’s reaction to a typical crash pulse. The headrest and the lateral supports of the seat were then reinforced. The previous tests were repeated, and the effects of the modifications were shown. The goal was to control the head and shoulder motion of the driver.

The results of these initial tests were shown to the various manufacturers of seats. They then submitted their own reinforced seats for evaluation. These early attempts showed that the manufacturers underestimated the head and shoulder’s ability to deform a reinforced seat during an impact event. With their new understanding of driver kinematics, the seat manufacturers have been producing seats that effectively control the head and shoulder motion of a driver during a crash. The effectiveness of a properly fitted seat and headrest configuration has become clearer as a result of barrier development testing.

Due to the highly restrained nature of the racecar driver and the high speeds associated with racing, the driver of a racecar is at particular risk to an injury known as basilar skull fracture. This injury results from large tension forces building up in the neck as the head whips forward relative to the restrained torso during a frontal impact. Sanctioning bodies are requiring drivers to wear approved head and neck restraints. To help these bodies identify suitable devices, WSU conducted a series of tests to compare the effectiveness of these devices.

It was found that of the 12 devices tested, only the HANS effectively controlled head whipping motion, and kept neck tension below the serious injury threshold. A limitation for all devices is the ability to function effectively when the force vector is greater than 30 degrees from full frontal. Under these conditions the headrest becomes a critical factor.

METHODS

Preparation

Tire-wall Barriers. The instrumentation for the tire barrier tests consisted of an accelerometer to measure the horizontal acceleration of the sled during impact, and a velocity transducer to measure the speed of the sled just prior to impact. A 16 mm high-speed motion picture camera was used to measure the deflection of the impacted stacks. The transducer outputs were conditioned by analog amplifiers, anti-alias filtered, and digitally stored for later analysis. All data were sampled at 10 kHz, and filtered according to SAE J211 specifications (SAE 2003).

Seats with integrated Headrests. In addition to measurement of sled acceleration and velocity, the reactions of a crash dummy were also measured. Depending on the angle of impact simulated, either a Hybrid III 50th male or a BioSid dummy was used as the driver surrogate. The dummies were instrumented such that three orthogonal axis of acceleration could be measured in the head, thorax, and pelvis. Additionally, a six-axis upper neck load cell was used to measure neck forces and moments. The appropriate thoracic deflection measurements and safety restraint loads were also collected. The data were collected using a self-contained on-board digital data acquisition system. Although these data were collected, the data were not used to evaluate seat performance and are not discussed in this paper.

Head and Neck Support Device. Testing of these devices used the same set-up as the seat testing previously described. The data collected were the same as in the seat tests.

Barrier Development. The barrier testing used the Hybrid III 50th male for all of the impacts discussed in this paper. The setup of the dummy was identical to the previously described sled testing, with the addition of six accelerometers to the dummy's head to complete the 3-2-2-2 configuration. Additionally, the vehicle dynamics were recorded by a tri-axial accelerometer array and a tri-axial rate sensor, both of which were mounted on the vehicle's left frame rail or an instrumentation tray mounted near the vehicle's center of gravity. All data were collected by an on-board digital data acquisition system, which sampled at 10 kHz.

Testing

*Tire-wall Barriers***.** Tire-wall testing was conducted at the Bioengineering Center in Detroit, Michigan. The WHAM III impact sled was used to impact stacks of tires arranged in trackside barrier configurations. Tires were stacked in various patterns according to the protocol (Table 1). The tires were either stacked against a rigid barrier (barrier backed) or, the stacked tires were placed 1.5 meters in front of the rigid barrier (freestanding). The sled was accelerated to a constant velocity and then released and allowed to impact the tire stacks. The front face of the sled was either left bare in order to concentrate the impact load (localized load) or, a rigid barrier was fixed to the front of the sled to distribute the load (distributed load). Three series of tire tests were conducted. Series 1 evaluated the basic properties of stacked tires. Series 2 evaluated tire stacks consisting of tires that had tires stuffed into them (tire in tire). Series 3 evaluated various methods of joining together stacks of tires, such as banding techniques. Series 1 and 2 consisted of impacting single and multiple stacks of tires, while Series 3 only consisted of multiple stacks of tires.

Table 1. Matrix of Tire Tests.

Configuration	Series 1	Series 2	Series 3
Barrier backed			
Distributed load	S/M	S/M	M
Localized load	S/M	S/M	M
Freestanding			
Distributed load	S/M	S/M	M
Localized load	S/M	S/M	M

S=single stack, M=multiple stack

Seats with Integrated Headrests Testing. Stockcar seat construction investigations were implemented on the WHAM III sled at the Bioengineering Center. The seats were tested under a variety of conditions (Table 2). Each configuration consisted of a modified Winston Cup Racing vehicle buck mounted on the surface of the sled. The buck was positioned at various angles in order to simulate impacts from pure frontal to pure lateral, with provision for mounting at 30, 45, and 60 degrees from frontal. In each test, either a Hybrid III 50th or a BioSid crash dummy was used, depending on the angle of impact. The Hybrid III was used in the pure frontal, 30, and 45 degree impacts; BioSid was used in the remaining tests. Each test consisted of accelerating the sled to a velocity of 35 mph, releasing it, and then decelerating it over a distance of 12 inches. The resulting crash pulse peaked at an average of 50 g's and lasted for 60 msec.

Table 2. Array of Seat Tests.

	Impact Angle (deg.)					
Manufacturer	0	30	45	60	90	180
Butler	X	X	X			
Butler 1					X	
Butler 2					X	
Butlernew					X	
PPI	X				X	X
Herzog						
Herzog Reinforced			X		X	
Eaton					X	
LaJoie	X	X	X		X	
ISP-Aluminum		X				
ISP-Carbon Fiber					X	
CorvetteCarbonFiber			X			
Kirkey				X		

*Head and Neck Support Device Testing***.** Using the best performing seat from the seat-test series, head and neck restraint testing was conducted using the same setup as the seat tests. The WHAM III sled with the NASCAR buck mounted at 30 degrees was subjected to the 50 g, 60 msec crash pulse. Some devices received additional testing (Table 3) The dummy was the hybrid III 50th male with a tri-axial or nine accelerometer array in the head, a six-axis upper neck load cell, tri-axial accelerometers at the sternal level, chest displacement potentiometer, and a tri-axial pelvic accelerometer array. The headrest of the seat was removed in order to negate its influence on neck tension.

Table 3. Array of Head and Neck Support Tests.

	Impact Angle (deg.)					
Manufacturer	0	30	45	60	90	180
HANS	X	X	X	X	X	X
Hutchens	X	X				
D-Cel		X				
White		X				
Wright		X				
Maloney		X				
Isaac		X				
G-force		X				
Simpson		X				
David Clark			X			
SafetySolutions		X				
Kintzi		X				

*Barrier Development Testing***.** Barrier development testing was conducted at the University of Nebraska-Lincoln, Midwest Roadside Safety Facility, Lincoln, Nebraska using full-scale Winston Cup and Indy Racing League vehicles. The vehicles were pulled into mockups of the SAFER barrier system by a tow cable and vehicle guidance system. An instrumented Hybrid III 50th dummy was mounted in the driver's seat of the vehicle. The vehicles were accelerated to speeds that ranged from 209 to 257 kph, released, and then impacted the barrier at angles that ranged from 20 to 30 degrees from pure lateral.

Analysis

Tire-wall Barriers. The impact acceleration and velocity of the crash sled were measured. The resulting acceleration data were used to derive impact force. Displacement was measured from the high-speed film. The displacement-versus-force data were then analyzed to determine which configurations dissipated the maximum amount of energy.

Seats with Integrated Headrests. The sled's impact acceleration and velocity were measured, along with the dummy's head accelerations, upper neck forces and moments, chest deflection and accelerations, and pelvic accelerations. Of interest in these tests was if the structure of the seat was rigid enough to resist the lateral motion of the dummy when subjected to the described crash pulse. Additionally, in the range where the head and neck supports are unable to function, a well-fitted seat and headrest combination should be able to reduce neck tension loads.

Head and Neck Support Devices. The critical measurement of interest was the peak neck tension generated during the impact event.

Barrier Development. Due to the complexity of the barrier tests, no single system was responsible alone for reducing injury potential for a given impact scenario. Still, neck tension was of particular interest, as it indicates the efficiency of the seat/headrest, combined with the other systems present. The impact trajectory of these tests was nearly lateral, which meant that the HANS device was not the major factor in controlling neck tension, but that the headrest was critical in controlling neck tension. The vehicle accelerations provided insight into the barrier performance. For the purposes of this paper, the head angular accelerations were computed, as well as HIC.

RESULTS

For tire-wall testing, typical reactions and energy absorptions are reported. For seat testing, the best performing designs are highlighted. For head and neck support devices, peak neck tension is given. For barrier development testing, the data from three tests are examined.

Tire-wall Barriers. From the 80 tire-wall tests conducted it was found that a typical configuration such as the type used at the Laguna raceway yielded an average impact force of 20 kN, and deflected a total of 1.5 meters. The force-deflection plot exhibited a psuedo-square wave shape.

Seats with Integrated Headrests. Seats from 8 different manufacturers were evaluated. It was found that the seats required a substantial amount of reinforcement to resist the loading of the dummy. A significant amount of structural material needed to be added to the seat, concentrating on the head and shoulder support region, but also to provide extra support in the pelvic region. Most manufacturers were able to achieve a suitable level of reinforcement. Of particular interest was a carbon fiber seat developed by PPI, Inc. The seat was designed to closely simulate the cockpit of an Indy Racing vehicle. The driver was completely surrounded by a seat and headrest that used energy absorbing materials to control head accelerations. The best performing seat, and one that could be modified for future testing, was a seat designed by the LaJoie Corporation. Figure 1 shows an early seat design and it's unsupportive nature along with the heavily reinforced seat developed by LaJoie.

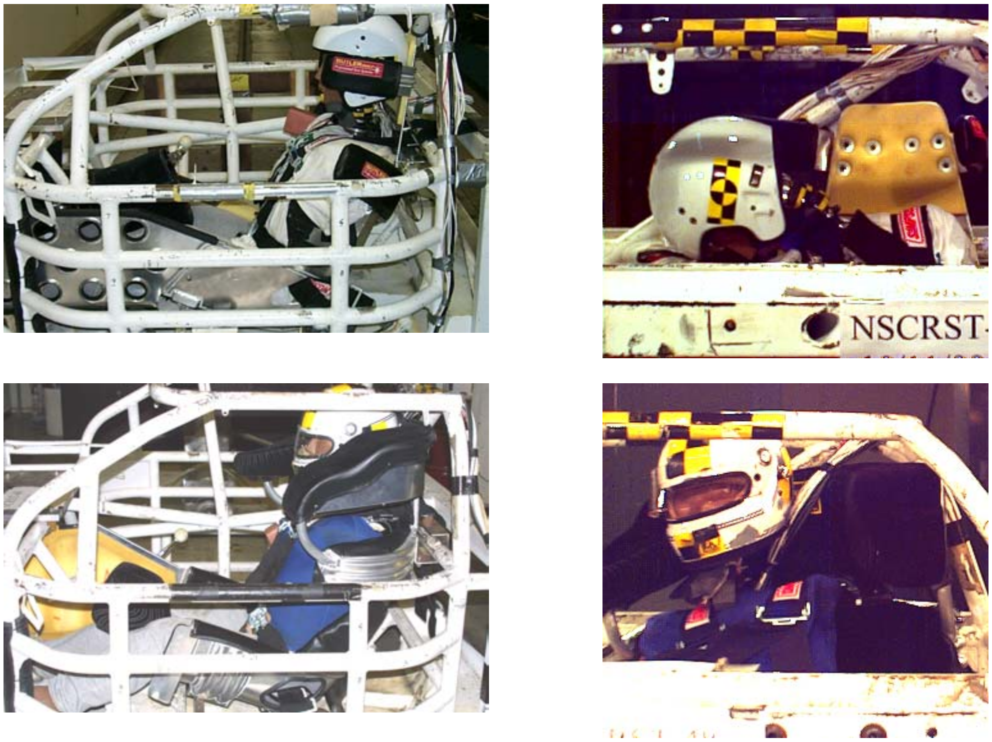

Figure 1: Seats and Their Dynamic Performance.

Head and Neck Support Device. A total of 12 different head and neck support devices were tested. Neck tension exceeded 2050 N for most devices. The peak tension for the best performing device, the HANS, was 0.75 kN. Forward head excursion for all other devices was exaggerated compared to the relatively small head excursion seen with the HANS device. The HANS and Hutchens devices are depicted in Figure 2.

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Figure 2: The HANS and Hutchens Head and Neck Support Devices.

Barrier Development. The results for three comparable Winston Cup vehicle impacts are given in Tables 4 through 6. The tests are designated IRL-21, 22, and 24. The average impact speed was 133 mph, and the impact trajectory was approximately 27 degrees from full lateral. The dummy in all three of these tests was instrumented with the 3-2-2-2 accelerometer array in the head. The results of the analysis of the head accelerations and the upper neck forces and moments are reported. Also included are the resultant accelerations of the vehicle. Figure 3 presents representations of typical test vehicles.

Figure 3: NASCAR Winston Cup and Indy Racing League Test Vehicles.

For the results as computed from the 3-2-2-2 accelerometer array output (Table 4): Test IRL-21 had a mid-sagittal plane angular speed of 31 rad/s, with a mid-sagittal plane angular acceleration of 2035 rad/s^2 and a coronal plane angular acceleration of 5199 rad/s^2. Test IRL -22 had a mid-sagittal plane angular speed of 32 rad/s, with a corresponding angular acceleration of 3284 rad/s^2 and a coronal plane angular acceleration of 9236 rad/s^2. Test IRL-24 had a mid-sagital plane angular speed of 19 rad/s, with a corresponding mid-sagital plane angular acceleration of 1677 rad/s^2 and a coronal plane angular acceleration of 2938 rad/s^2.

Based on the tri-axial acceleration measurement taken at the center of gravity of the dummy's head (Table 4): Tests IRL-21 had a HIC$_{15}$ of 1484 with a resultant acceleration of 128 g. Test IRL-22 had a HIC$_{15}$ of 1360 with a resultant acceleration of 123 g. Test IRL-24 had a HIC$_{15}$ of 541 and a resultant acceleration of 72 g.

Table 4. Head Kinematics.

Test	Res. (G)	HIC_{15}	$\dot{\omega}_x$ (rad/s/s)	$\dot{\omega}_y$ (rad/s/s)
IRL-21	128	1484	5199	2035
IRL-22	123	1360	9236	3284
IRL-24	72	541	2938	1677
IARV	180*	700[#]	16000[§]	4500[¥]

*(Mertz and Irwin, 2003)

[#] 49 CFR Ch.V 571.208(2003), and (Mertz and Irwin, 2003)

[§] (Margulies, 1990) – coronal rotation

[¥] (Ommaya, 1984)- sagittal rotation, $\omega < 30$ rad/s

The upper neck loads (Table 5) and moments (Table 6) were measured with the upper neck load cell. Test IRL-21 had a peak X-direction load of 994 N. The peak Y-direction load was 832 N. The peak axial loads were 4341 N and -1462 N. Test IRL-22 had a peak X-direction load of 2119 N. The peak Y-direction load was 1281 N. The peak axial loads were 5117 N and -176 N. Test IRL-24 had a peak X-direction load of 369 N. The peak Y-direction load was 279 N, and the peak axial loads were 1709 N and -24 N.

Table 5. Measured Peak Neck Loads.

Test	Fx (N)	Fy (N)	+Fz (N)	-Fz (N)
IRL-21	994	832	4341	1462
IRL-22	2119	1281	5117	176
IRL-24	369	279	1709	24
IARV*	3100	3100	4170	4000

*49 CFR Ch.571.208(2003), (Mertz and Irwin, 2003)

Table 6. Measured Peak Neck Moments.

Test	Mx (Nm)	+My (Nm)	-My (Nm)	Mz (Nm)
IRL-21	47	38	41	30
IRL-22	66	3	65	26
IRL-24	32	10	25	11
IARV*	143	190	96	96

*(Mertz and Irwin, 2003)

The peak vehicle dynamic data measured from a tri-axial accelerometer array is as follows: Test IRL-21 had a lateral acceleration of -67 g's. Test IRL-22 had a lateral acceleration of -53 g's. Test IRL-24 had a lateral acceleration of -77 g's. The lateral accelerations are the predominant acceleration in these impacts. Additionally, for test IRL-22, only lateral acceleration was available making it the only parameter comparable between the three tests.

DISCUSSION

Tire-wall Tests. Tire stacks and tire-walls exhibited generally efficient energy dissipation characteristics. They make an economical barrier, due to the fact that scrap tires can be used for their construction. A drawback is that tire-walls occupy a large space, which makes them undesirable for closed oval courses like the Indianapolis Motor Speedway. Another drawback is that vehicles can get snagged by these walls and then ejected in unpredictable trajectories.

Seats with Integrated Headrests. A well-reinforced seat that is properly fitted to the driver can effectively control driver kinematics during an impact. Lack of deformation during a lateral impact is a key factor for an effective seat. Additionally, a reduction in neck tension indicates that the seat was well fitted to the driver. This was illustrated during barrier development testing, were it was shown that if the headrest properly restrained the dummy's head the result would be a reduction in neck tension.

Head and Neck Support Devices. Although many head and neck support devices were submitted for evaluation, only one could satisfy all the parameters for controlling driver head kinematics during a frontal impact. The HANS device outperformed all other devices by effectively reducing neck tension and limiting forward head excursion and whipping.

Barrier Development. It has been shown in barrier testing that it is possible to reduce neck loads and head accelerations below a level were serious injury is likely to occur. This is demonstrated by the results of IRL-24, where the neck tension loads are well below the serious injury threshold. The major difference between tests IRL-21 and IRL-22 versus IRL-24 is that the seat was better fitted to the dummy. Because the headrest supported the dummy's head, neck tension remained relatively low.

CONCLUSIONS

The results from these investigations show that with the application of crash protection research methods it is possible to develop the right combinations of energy absorbing barriers, reinforced seats, head and neck supports, and other safety devices, to achieve levels of safety that previously were unavailable to the motorsports participant.

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DISCUSSION

PAPER: **Advancing Racing Safety: An Overview**

PRESENTER: ***Craig Foster, Bioengineering Center, Wayne State University***

QUESTION: *Erik Takhounts, NHSTA*

Okay. So those high hits that you observed there are probably due to the head contact with the structure. that's your hypothesis.

ANSWER: I wouldn't say that was my hypothesis, but I couldn't say for sure.

Q: Okay. Thank you.

QUESTION: *Guy Nusholtz, DaimlerChrysler*

Just to follow up a little bit on Erik's question: Do you see a discontinuity in acceleration response? That would be an indication, you know. If you're traveling along at 30 g's and all of a sudden in a millisecond or so, you're up another 50 or 100, that would indicate that you might have hit something hard. Or, did anybody look at the time histories? I guess that's the first question..

A: Well, not that I'm aware of.

Q: Okay. Second question is: Did you do a comparison between different dummies, so a Thor dummy and the Hybrid III to see if the results are dummy-dependent?

A: Well, we just started using Thor actually in our lab on the sled and now we're taking it out to Nebraska to put it in some vehicles in there. I couldn't quantify any difference between them, but there is a difference when you look at video as to what the dummy's motion looks like. And, Thor seems to look much more realistic than Hybrid III.

Q: Okay. So your results could be, then, dummy-dependent.

A: Could be.

Q: And then, the question would be: Which dummy is actually—and I think you partially answered that, at least subjectively. The Thor looked better. Is that correct?

A: Visually, sure.

Q: Visually. Okay. An interactive eyeball correlation. [laughter]

A: I'm sorry. I didn't understand that. [laughter]

Q: Never mind. You don't need to! [laughter]

QUESTION: *Peter Martin, NHTSA*

I was just going to ask about the Thor, as well. Could—In the limited testing that you've done with Thor, could you comment please on the ability of Thor to discriminate between those eight version of the HANS device and the 10 versions of the seats and so forth?

A: Well, I think that due to the advanced nature of Thor, he may be able to more closely simulate the human than the Hybrid III does. So, you could maybe get more valid results from Thor versus the Hybrid III.

Q: Thanks.

A: You're welcome.