

**Guided Fall Impact Test Devices
Monorail and Twin-Wire System Comparison
Draft E.B. Becker, May 1, 1997**

Introduction

The Snell Memorial Foundation's test laboratory in North Highlands, California, recently participated in an inter-laboratory test series intended to determine the comparability of twin-wire and monorail impact test devices. A portion of the tests consisted of a series of impacts between an aluminum sphere and a modular elastomer programmer (MEP), a resilient pad known for the stability of its material properties. The technicians took pains to use the same instrumentation and to reproduce the same drop masses on both the twin-wire and monorail devices so that any differences in the test results could be ascribed only to the differences between the monorail and twin-wire devices themselves.

The tests revealed a five percent difference in peak impact accelerations obtained by the two systems. The monorail system obtained peaks on the order of 420 g while the twin-wire obtained 400 g for the same impact velocities. This result is highly repeatable. However, the differences in the impact response involve more than just the peak value. Since the entire impact response for either system is also highly repeatable, the remainder of this development will consider and compare entire traces in order to identify the sources of the difference in peak acceleration and to determine the implications of these differences.

The Impact Devices

One of the central considerations in crash helmet evaluation is impact protection. How well will a helmet protect its wearer from a sharp blow to the head? One of the most common tests for impact protection requires that the helmet be placed on a metal head form of specified properties and that the helmeted head form be dropped to collide with an unyielding surface at a specified impact velocity. The acceleration imparted to the head form is measured throughout the event by an accelerometer mounted at the head form center of gravity. The time history of the measured head form acceleration is then analyzed to determine the performance of the helmet.

The most commonly used systems in the United States are guided fall systems. A partial head form simulating portions of the head above the Frankfort plane is attached to a simple frame that slips vertically along mechanical guides. A socket in the base of the

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head form mates with a ball fixed in the frame so that the head form may be positioned in a range of orientations. Since the accelerometer is mounted in the ball, its position in the head form and its alignment with respect to the frame is assured.

The frame then maintains the orientation and horizontal alignment of the head form as it falls to the impact surface. The advantage of these guided fall systems is that they allow close control of the impact event and the use of a relatively simple single-axis acceleration transducer.

There are two classes of guided fall devices in current use. The principal difference between them is in the nature of the guidance. Monorail systems employ a single rail mounted along a girder. The monorail is very rigid and constrains the motion almost completely to pure translation along the vertical axis. The system permits very little angular displacement about any of the horizontal axes.

Twin-wire systems use two parallel wires stretched between the ceiling and the massive reaction block fixed in the floor. The twin-wires are flexible so that even when set to 300 lbs of tension they allow quite a bit of horizontal translation and rotation in response to impact.

The frames for the two systems are also different. The monorail system employs a metal housing containing two linear bearings and a cylindrical socket that accommodates the arm of the ball arm assembly. The mass of this housing is located primarily at the monorail itself well away from the accelerometer and the head form's design center of gravity. It is quite difficult to compensate for the housing mass given the symmetries and constraints on the ball arm and other hardware.

The twin-wire frame, often called a drop arm, spans the 18" gap between the two wires so that its mass is distributed on either side of the vertical axis that passes through the head form's design center of gravity. This span also results in a much greater moment of inertia for the total drop assembly. As a result, the mass distribution problems encountered in monorail devices are greatly simplified. However, the drop arm span incurs other problems.

The various limitations on the drop arm design preclude a sufficiently stiff assembly to behave as an ideal rigid body. As

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a result, a poorly designed drop arm may flex considerably during impact causing the drop arm to bind on the wires. Better designs limit this flexing but still contain resonant frequencies. That is, the drop arm will ring after an impact much like a tuning fork. This residual ringing may be noted on the accelerometer traces following some test impacts.

The Comparison Tests

The Consumer Product Safety Commission (CPSC) proposed a series of tests to investigate the behavior of monorail and twin-wire test devices in order to evaluate their capabilities as helmet test devices. It is expected that one of the outcomes of this investigation will be a rationale for determining whether certain test devices or classes of test devices are appropriate for bicycle helmet testing.

Several different organizations, including the Snell Memorial Foundation, participated in performing various tests using monorail and twin-wire impact devices. Test data was sent directly to CPSC for analysis but CPSC has promised to distribute copies to all the participants at some later date. However, since the Foundation performed testing on both monorail and twin-wire devices, it is possible at this time to compare results for a single configuration of each general class.

Since only a single configuration of each class is considered, this comparison will lack the scope of the more general CPSC investigation. However, this disadvantage may be amply compensated by the control the Foundation's technicians were able to exercise over extraneous factors affecting test results.

The same instrumentation was used for both test series. Once testing had been completed on one device, the accelerometer, velocity gate and instrumentation rack were disconnected, wheeled over and installed on the other device. As a result, this comparison is between mechanical guidance systems and is unclouded by instrumentation artifact and bias.

This comparison considers only one portion of the CPSC testing, the sphere/MEP impacts. In these tests, the head form was replaced with an aluminum sphere with a 5.75" radius while the anvil was replaced with a resilient modular elastomer programmer (MEP) pad. The MEP is known for its stable mechanical properties particularly

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its repeatable force versus dynamic deformation behavior. CPSC provided a single MEP pad which all the participants impacted in turn.

The spherical impactor presents the same impact profile to the MEP regardless of orientation. Furthermore, since the MEP is homogeneous, the distribution of forces exerted by the MEP on the surface of sphere during impact will total to a single vector along the vertical axis through the center of the sphere.

This development considers only the first 16 impacts collected. No attempt was made to select from among the data sets collected. There is no anticipation that any of the other data sets differs in any significant manner from those used in the analysis.

The data for each impact in Foundation's test series consist of impact velocity, that is, the time taken for a 20 mm tab to pass through a light beam just prior to impact, plus 1024 points of digitized acceleration signal collected at 50,000 samples per second.

Test Results

For similar impact velocities, the peak accelerations obtained on the monorail system were uniformly higher than those obtained on the twin-wire system. The difference amounted to about 5%.

The general shapes of the impact portion of the traces for the monorail and twin-wire systems seemed very similar. The first few impacts in either series may be at impact velocities substantially lower than desired but, even so, the shapes of these traces agreed quite well with those later in the series. Within each series, the similarity of the traces was remarkable. Features well after the impact event that appeared to be purely accidental repeated almost identically in test after test.

Figures 1. and 2. show the results for the monorail and twin-wire systems as acquired. The only manipulation imposed is a linear interpolation between data points to align the various onsets of impact.

Analysis

The similarities between the two sets of responses suggests that

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each set of responses be treated as the sum of an ideal acceleration time history plus an artifact imposed by the guidance system:

$$\begin{aligned} A_{\text{monorail}} &= A_{\text{ideal}} + N_{\text{monorail}} \\ A_{\text{twin-wire}} &= A_{\text{ideal}} + N_{\text{twin-wire}} \end{aligned} \quad (1)$$

Where 'A' represents the time histories of acceleration and 'N' represents the system artifacts. This development will attempt to identify the artifacts peculiar to both systems.

The most prominent difference between the two sets of traces is the residual sinusoid on the twin-wire traces continuing on well after the impact event. This sinusoid has a frequency of about 200 Hertz. Since it is observed well past the point that the sphere has rebounded from the MEP and since the frequency is well beyond that that might be expected from interaction with the twin-wires, this sinusoid is ascribed to resonance in the twin wire drop-arm.

Since it was evident that the impact was exciting at least one resonance in the drop arm, it was thought at first that these resonances might account for the difference in peak accelerations. The drop-arm/sphere assembly was modeled as a system of two masses joined by a linear spring and selected mass and spring properties consistent with the 5% difference observed in the peak accelerations.

The equations provided in the appendix develop a deconvolution that may be applied to the acceleration of a two mass system to solve for the input force as a function of time. Dividing this force by the sum of the two masses yields the acceleration time history for a single mass system when acted on by the same input force. Although it may be argued that the force is not properly a function of time but is instead a function of the displacement of the sphere into the MEP, the difference is slight. Essentially, the operation removes the effects of the specified resonance parameters from the acceleration output.

The next step was to search for resonances in the drop-arm/sphere assembly. The assembly was removed from the wires and suspended while being struck with a heavy mallet. We were able to excite ringing at about 200 cycles per second and 450 cycles per second.

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Finally we applied the deconvolution for each of these frequencies and for a range of mass parameters in order to determine whether we could remove the residual sinusoid from the acceleration output and restore the missing 5% of the peak acceleration. Mass parameters removing the residual sinusoid were readily identified and seemed quite consistent with the design of drop-arm.

However, we were not able to find any parameters that would account for the peak acceleration difference. Furthermore, it appears that the higher resonance is not excited by impacts with the MEP, that is, any non-zero mass specification imposes a residual ringing on the deconvoluted acceleration.

The deconvolution that reduces the residual sinusoid implies that about 2.5% of the impact energy is missing. That is 2.5% of the kinetic energy stored in the falling drop-arm/sphere does not go into compressing the MEP pad but instead is absorbed by flexure in the drop arm. The deconvolution actually lowers the peak acceleration about three or four g's. However, if the energy losses are taken into account, a perfectly rigid drop arm should intrude slightly further into the MEP and obtain peaks one or two g's greater than those actually measured. This is a long way from the 20 g difference observed for the monorail.

We also studied the monorail system for resonances. There are no significant resonances in the drop assembly. It seems unlikely that there is any resonance involving the monorail/girder although other mechanical interactions may be present.

The next likely source of the different peak accelerations was thought to be the mass distributions of the drop apparatus. A second appendix develops an analysis of impact in which the center of gravity of the falling body is removed from the axis of the impact force. The analysis reveals that the accelerations are increased by a constant factor based on the displacement of the center of gravity from the center of the sphere, the mass of the system, and the system's moment of inertia in the vertical plane containing the center of the sphere and the system center of gravity. The essence of the development is that the force induces a rotational acceleration as well as a translational acceleration. Since the accelerometer is displaced from the center of gravity, its signal includes the translational acceleration plus the rotational acceleration multiplied by its horizontal displacement.

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Estimated values for the displacements and mass moments suggested that the accelerations for the monorail system should be approximately 10% higher than those of the twin-wire. The data indicated a 5% difference. The twin-wire peak acceleration now appears to be 20 g's too high.

However, the monorail system limits the angular travel of the drop assembly. The calculations also indicate that the drop mass should come up to these limits after no more than 1 to 1.4 milliseconds into the impact. If c.g. displacement and bearing interference are perturbing the monorail response, it should be possible to subtract the twin-wire acceleration from the monorail acceleration and isolate these effects.

The sixteen traces from each test series were time shifted and averaged. Since a few of the impacts in each series were at different impact velocities the following manipulation was performed to eliminate this source of variation. Each of the sixteen traces in each series was multiplied by a scaling factor to obtain a best fit with the averaged trace. Then the scaled traces were treated in the usual manner to obtain a new average trace and an RMS deviation trace for both the monorail and twin-wire series.

These new average traces were subtracted from each other to obtain a new trace consisting solely of a combination of the artifacts imposed by both systems.

$$\begin{aligned} A_{monorail} - A_{twin-wire} &= A_{ideal} - A_{ideal} + N_{monorail} - N_{twin-wire} \\ &= N_{monorail} - N_{twin-wire} \end{aligned} \quad (2)$$

So long as the artifacts can be considered as minor perturbations on the ideal response, the difference in the traces may yield useful insights into both systems.

The difference between the traces and bounds calculated from the RMS deviations are shown in figure 3. The figure also includes the averaged monorail trace divided by 10.0 to illustrate the timing of features in the difference. Figure 4. shows the difference for the impact portion of the trace. Figure 4. also includes both averages, now divided by 20.0 and a portion of the monorail trace divided by 10.0. The agreement between this one tenth monorail

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onset and the difference between the two traces is striking. The c.g. displacement calculations indicate that the monorail output should be approximately 10% higher for the first millisecond or so of the impact. The difference in the outputs of the monorail and twin-wire reflect this 10% increment and also seem to show mechanical interference at about the same point that bearing interference was predicted for the monorail system.

Although it is possible that the source of the observation is a 10% negative artifact on the twin-wire system, such an artifact could not possibly arise from resonance. The nature of resonance is that the effective mass of the impactor is initially lower than its total mass so that the onset of the acceleration trace should be higher than expected. Similarly for c.g. displacements, the accelerations must be higher than expected. The only exception is for geometries in which the center of gravity falls between the force axis and the location of the sensitive element of the accelerometer, a condition that is not true for either system.

Conclusions

The 5% higher peak accelerations observed for the monorail system are due to a combination of effects arising from the c.g. displacement and interference between the bearings and the rail itself.

A simple torque calculation suggests that each of the two linear bearings in the monorail housing is subjected to forces of at least 1000 lbs during the impact. A review of the bearing catalogs indicates that the bearings generally used are rated only for 250 lbs of dynamic load.

The resonances in the twin-wire system produce deviations of about two to three g's from what might be expected of a perfectly rigid system. These deviations depend greatly on the shape and amplitude of the impact acceleration. Since helmet testing generally involves lower amplitude signals with lower frequency content, it is expected that the minimal deviations seen here will be even smaller. Deconvolution of representative helmet impact traces supports this conjecture.

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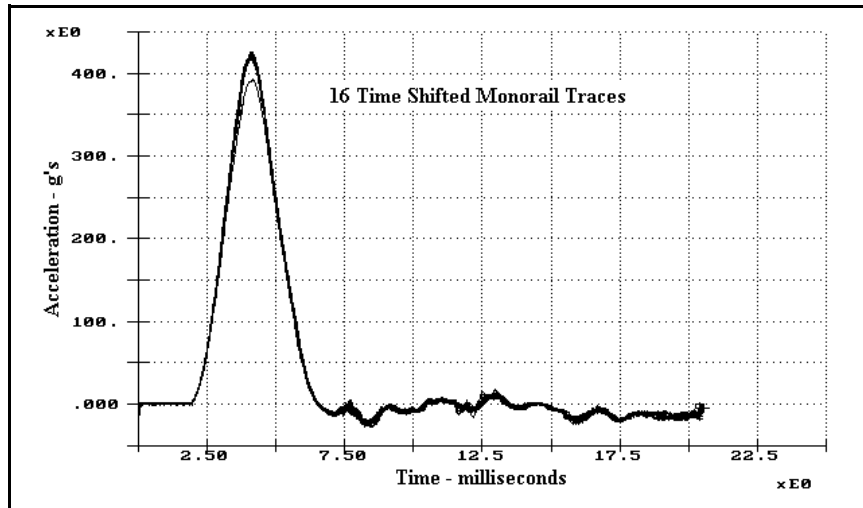


Figure 1. Time Shifted Monorail Accelerations

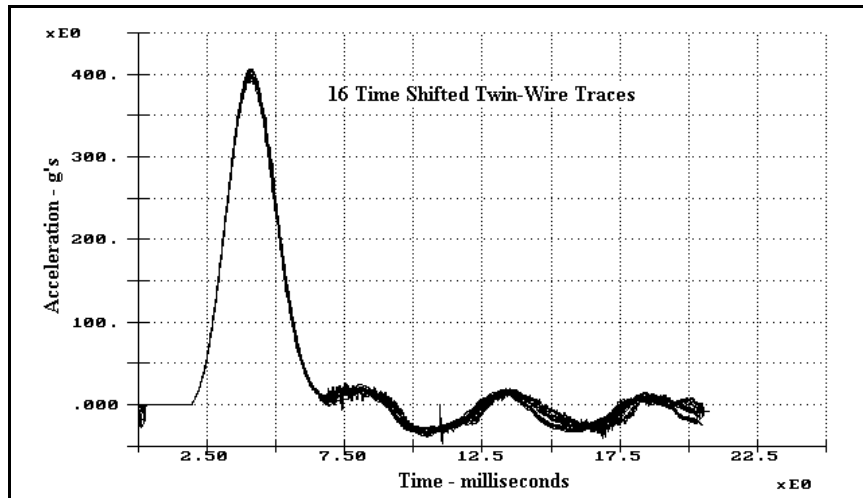


Figure 2. Time Shifted Twin-Wire Accelerations

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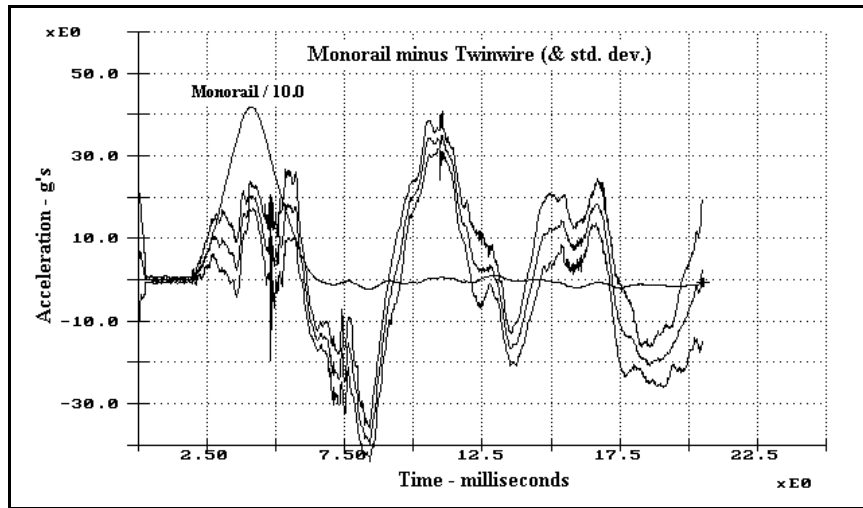


Figure 3. Monorail minus Twin-Wire - General

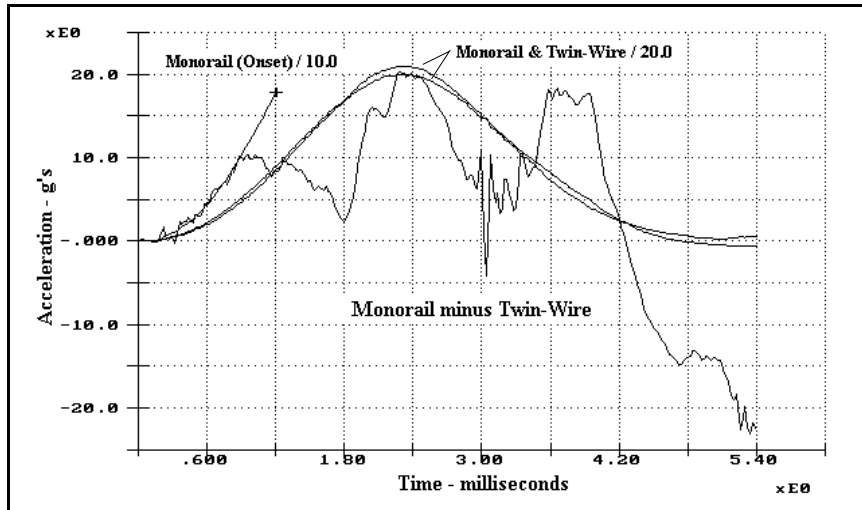


Figure. 4 Monorail minus Twin-Wire - Detail