PHANTOM®

WHITE PAPER

Automotive Crash Test Imaging Fundamentals

Best practices for on- and off-board vehicle crash tests

As the automotive industry continues to evolve its vehicle safety requirements, it is becoming increasingly necessary to analyze crash tests with extreme precision—requiring the latest in high-speed imaging. Slowing down the crash footage enables automotive engineers to observe and analyze subtle motion details in airbags, seatbelts and other components. This ability helps them make critical design decisions and also make vehicles safer.

Crash tests have unique requirements, mostly due to a fixed test environment and the need for multiple views of large and small elements moving within that space. Technicians must pay careful attention to lighting, field of view, depth of field and lens selection. *(For more information about these and other imaging concepts, see our sidebar.)* In this article, we will explore some of the imaging rules of thumb that can help camera operators optimize high-speed images for on-board and off-board crash tests.

We will also introduce and discuss some high-speed cameras currently on the market that excel in automotive crash testing—helping engineers make vehicles safer and optimize component design.

DEVELOPED BY:

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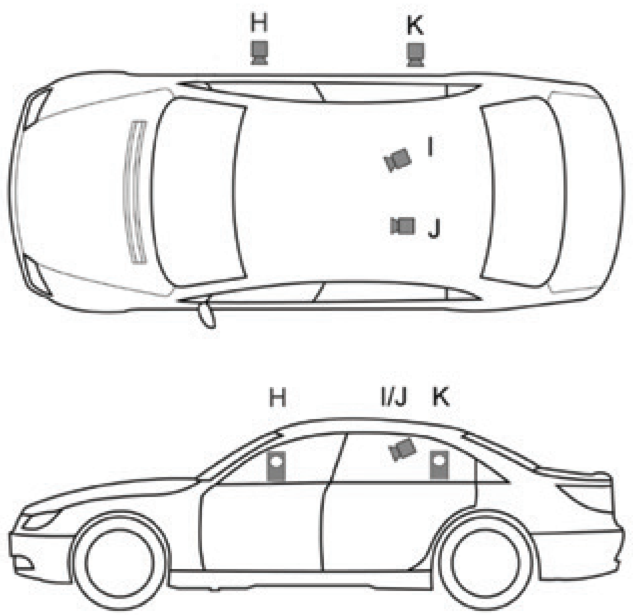
CRASH TEST IMAGING GOALS

Automotive crash tests typically have one of two goals. The first is to ensure the vehicle is safe as determined by industry safety standards—including those specified by agencies such as the Insurance Institute for Highway Safety (IIHS), National Highway Traffic Safety Administration (NHTSA) and New Car Assessment Program (NCAP), to name a few. Each agency outlines the imaging requirements, including how high-speed cameras must be positioned in and around the vehicle undergoing testing.

One example is the Small Overlap Frontal Crashworthiness Evaluation by the IIHS, which applies to driver and passenger-side overlap crash tests. According to this protocol, which replicates what happens if the front corner of the vehicle collides with an object, high-speed cameras must meet the following focal points and focal lengths when mounted inside the vehicle:

- Side view of the driver—10 millimeters
- Over the driver's shoulder—16 millimeters
- Rear view of the driver—16 millimeters
- View of string potentiometers and instrumentation—10 millimeters



On-board camera positions for the IIHS Small Overlap Frontal Crashworthiness Evaluation include: front passenger door (H), inside roof on the passenger (I) and driver (J) sides and rear passenger door (K).

Depending on the particular IIHS test, as many as 16 cameras may be used—each one capturing a different aspect of the crash. Crash tests also serve an engineering purpose, enabling automotive engineers to conduct design testing, as well as standalone airbag and component testing. Cameras are selected and positioned to specifically gather the required information.

Making an Impact in Automotive Crash Tests

Thanks to their fast frame rates, high pixel resolution and compact, rugged construction, the following cameras shine in on-board and off-board automotive crash tests:

- The **Phantom Miro C320** and **C320J** are small, durable and light-sensitive—making them a perfect fit for on-board crash tests. These cameras can withstand shock forces up to 170G and come with an internal backup battery, ensuring test images are captured and saved in the event of an impact-related power loss. These cameras can capture 1,400 fps at 1920 x 1080.
- The rugged **Miro C210** and **C210J** excel in capturing tight on-board shots. Their 1.3-megapixel sensor features tightly packed 5.6-micron pixels at 12-bit depth to produce highly detailed images at high speeds. Like the C320, they integrate an internal battery and Flash to protect critical data. These cameras can capture 1,800 fps at 1280 x 1024.
- At 1-inch cubed, the **Phantom Miro N5** is the smallest Phantom camera—making it ideal for the most demanding on-board crash tests. This camera includes three interchangeable components, including the camera head equipped with a 0.5-megapixel sensor, CXP cable and Miro N-JB base.
- The **Phantom VEO 440** features a 4-megapixel sensor—providing high resolution, greater image coverage and detail in off-board crash tests. Choose from a variety of lens mounts, including F, C and Canon EF mounts with electronic lens control. These cameras can capture 1,100 fps at 2560 x 1600.

COMPLETE FAMILY OF CRASH TEST SOLUTIONS

Delivering superior Phantom image quality in both on-board and off-board setups

Crash Tests and High-Speed Data Acquisition

When it comes to crash tests, high-speed cameras do not always operate alone. To characterize various aspects of crash tests, automotive engineers have traditionally relied on accelerometers and other analog and/or digital sensors. Now, Vision Research has made it easier than ever to add high-speed imaging into this mix. The company has implemented a direct link between its Phantom high-speed cameras and third-party data acquisition (DAQ) systems—allowing crash test engineers to collect analog or digital data and video data simultaneously. This ability lets them visualize the synchronized video and data side by side within the Phantom Camera Control (PCC) software—leading to new insight into the event at hand.

ON-BOARD TESTS— CAMERA DESIGN, FIELD OF VIEW AND DEPTH OF FIELD

The specific imaging goal of the crash test will determine the camera position, whether on-board—inside the vehicle or sled—or off-board.

Due to their location inside the car, on-board crash tests require small, lightweight and durable cameras that can easily fit in tight spaces while withstanding repeated G-forces. The Phantom Miro C320 camera, for example, is designed and tested to withstand up to 170G. It is housed in a compact, yet rugged 1.2-pound package and meets MIL-STD 202G specifications. While an ability to withstand 100G is standard, most vehicle crashes fall between 30 and 75G.

Small specialty cameras can also be used for tight spaces, such as inside door panels or near the brake pedal. A camera head with only the sensor is tethered to a larger, separate control base—creating a very small, lightweight form factor. One example is the Phantom Miro N5, which includes a 1-inch cube camera tethered via a CXP cable to a control base where images are instantly and safely stored.

The advantages of small specialty cameras include:

- Placement almost anywhere in the vehicle, including the engine and undercarriage
- Light weight, which facilitates easy mounting with duct tape or VELCRO®
- High crash survival rates, as the small units often escape damage

Small specialty cameras also have disadvantages. For one, the exposed tether cable can be a point of failure. One way to mitigate the risk is to ensure images are downloaded to the base immediately via a CXP cable. In addition, the sensor and pixels are often small—requiring additional lighting. Targeted LED lighting helps this situation.

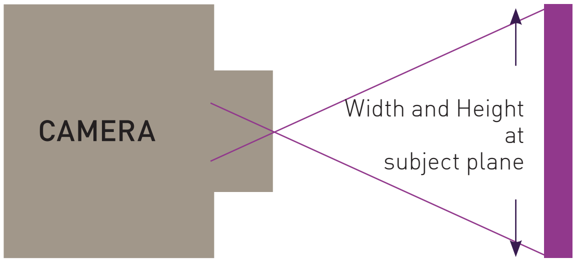
Generally, on-board tests are limited in terms of available lighting. To overcome this challenge, it helps to select high-speed cameras that have an excellent dynamic range—enabling technicians to see nuanced shades of black on a brake pedal, for example, or shades of white in a deployed airbag.

Other important considerations for on-board crash tests include:

Field of view (FOV). Because high-speed cameras are mounted in close proximity to their objects of interest—whether the crash dummy, dashboard or seatbelt—technicians require cameras with a wide FOV. The FOV depends on several variables, including lens selection, recording resolution and the distance between the camera and focal plane.

For example, according to the Vision Research online lens calculator, if we need a FOV of 5 feet and set the Phantom Miro C320 to full resolution (1920 x 1080), then we need a lens with a horizontal focal length of 18 millimeters and a vertical focal length of 10.72 millimeters. If we change the camera position to 7 feet away, now we need a lens with a horizontal focal length of 26.55 millimeters and a vertical focal length of 15.01 millimeters. Changing one variable changes the others.

Bear in mind, camera models may be different due to the sensor size, and the lens format must match the sensor format.



Depth of field (DOF). While the DOF should be deep enough to let technicians see clearly across the car, there is a tradeoff with lighting. A higher aperture provides a larger depth of focus but with darker images. The maximum DOF is achieved with the highest f-stop of the lens, which corresponds to the smallest opening. Conversely, the smaller the f-stop number, the larger the aperture size, resulting in brighter images with a shallow DOF. In order to achieve an adequate DOF, supplemental lighting is key. This is where high-intensity LED lights become critical to automotive crash testing. These lights are often customized for the area illumination requirement.

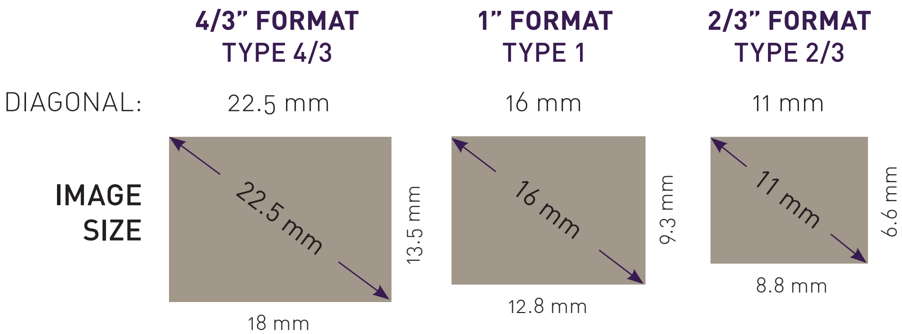
Although lighting is usually necessary in high-speed imaging, high-speed cameras that are designed to utilize as much light as possible can decrease the need. The Phantom Miro C320, for example, integrates a CMOS sensor with tightly packed 10-micron pixels for greater light sensitivity. It also features high ISO ratings—10,000D (monochrome) and 2,000D (color)—which means less supplemental light is required to capture high-quality images.

LENS CONSIDERATIONS FOR ON-BOARD TESTS

On-board crash tests usually utilize C-mount lenses, which are often inexpensive and are small enough to withstand repeated impact—making them the ideal choice for on-board crash tests.

Selecting the right lens depends on the camera's sensor format which is calculated from the sensor's resolution and pixel size. The sensor size, along with the resulting image circle diameter, are often measured in metric but referred to in inches. Example scenarios include:

- A 2/3-inch sensor format has an 11-millimeter diagonal—requiring a lens with a minimum image circle of 11 millimeters in diameter to cover the sensor, or a 2/3-inch format.
- A 1-inch sensor format has a 16-millimeter diagonal—requiring a lens with a minimum image circle of 16 millimeters in diameter to cover the sensor, or a 1-inch format.
- And finally, a 4/3-inch sensor format has a 22.5-millimeter diagonal—requiring a lens with a minimum image circle of 22.5 millimeters in diameter to cover the sensor, or a 4/3-inch format.



High-speed camera sensor sizes and corresponding lenses.

A 4/3-inch lens is required to use the Miro C320 at full resolution, for example, while the Miro C210 uses a 1-inch lens. Using a lens that is larger than what the sensor requires will cover the sensor, however there will be a "crop factor" to calculate. For example a 20-millimeter 4/3 lens will equate to 40-millimeter lens coverage on a 2/3 inch sensor. It is even more important to avoid using lenses that are too small for the sensor, as this combination will blacken the corners of the image—an effect known as vignetting. For example, a 2/3-inch C-mount lens should be mounted on a camera with a 2/3-inch sensor, but attaching the same lens on a camera with a 1-inch sensor would result in vignetting.

No vignetting versus vignetting.

The following lenses are also used in on-board crash testing:

- **S (M12) mount lenses.** S-mount lenses are ideal for small specialty cameras because they are very small, typically inexpensive and available in a variety of focal lengths. Operators can focus these lenses by screwing them into the camera close to the sensor and then locking them with a lock-nut.
- **Micro-four thirds (MFT) lenses.** MFT lenses are newly developed cost-effective alternatives to the heavy, large 4/3-inch lenses used in larger camera sensor HD imaging.

LENS CALCULATION EXAMPLE: CAPTURING OVER THE SHOULDER AIRBAG DEPLOYMENT

To select the correct lens in this scenario, we first need to consider the object of interest—including how far away it is from the camera—as well as recording resolution. The formulas to calculate the correct lens can be cumbersome. For example, here are the formulas for the Phantom Miro C320 camera:

HORIZONTAL =

$$((D \times 304.8) \times ((10 \times P_h)/1000)/(F_h \times 304.8))/(1+((10 \times P_h)/1000)/(F_h \times 304.8))$$

WHERE:
D = Distance in feet from object
P_h = Horizontal pixels
F_h = Horizontal field of view

VERTICAL =

$$((D \times 304.8) \times ((10 \times P_v)/1000)/(F_v \times 304.8))/(1+((10 \times P_v)/1000)/(F_v \times 304.8))$$

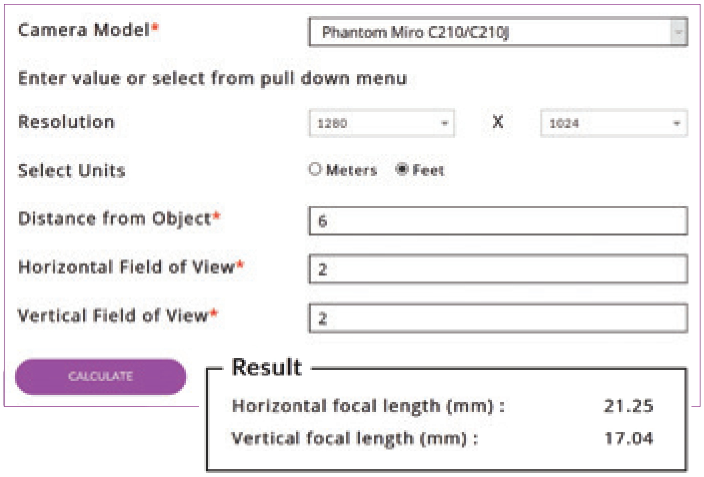
WHERE:
D = Distance in feet from object
P_v = Horizontal pixels
F_v = Horizontal field of view

However, Vision Research makes this process easy by offering a free lens calculator on its website. This tool is built to specifically work with the custom sensors used in Phantom cameras.

In this case, we want to position a Phantom Miro C210 high-speed camera so that it peers over the shoulder of the driver to observe the airbag located roughly 4 to 5 feet away from the camera. First, we pull up the lens calculator, select the camera model and then type in the horizontal and vertical resolutions. Because we want to observe the airbag—which is a larger area—we want to use the camera's full resolution of 1280 x 1024.

Next, we enter the distance from the subject (6 feet), the length of the horizontal FOV (2 feet) and the height of the vertical FOV (2 feet). Finally, we can select "calculate," which generates the following values: horizontal focal length—21.25 millimeters and vertical focal length—17.04 millimeters.

Since the two numbers differ significantly, we can either select an average focal length between the two, or bias the lens toward either the horizontal or vertical FOV—depending on application needs and preferences.



The Vision Research lens calculator.

IMAGING CONSIDERATIONS FOR OFF-BOARD CRASH TESTS

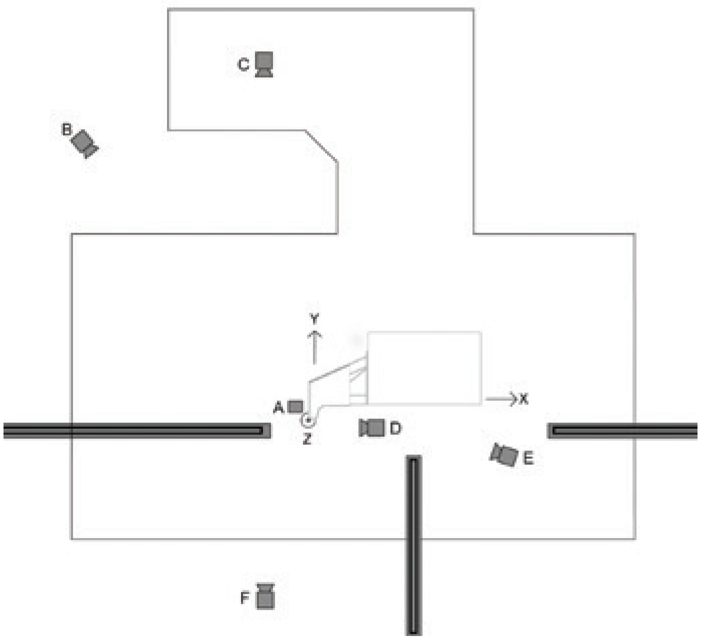
Next, we turn our attention to off-board crash tests, which involve mounting high-speed cameras farther away from the vehicle—usually ranging from 5 to 15 meters—to capture it from the side, top, front or bottom. The IIHS Small Overlap Frontal Crashworthiness Evaluation, for example, includes the following coordinates and lens focal lengths for six off-board cameras:

Coordinates, Focal Points and Settings

Camera Position	*Over-head*	*Rear Oblique*	*Left Side*	*Front*	*Front Oblique*	*Right Side*
Coordinate X *(cm)*	0	-712	-127	232	892	-102
Coordinate Y *(cm)*	0	1030	1410	-58	-318	-1543
Coordinate Z *(cm)*	910	125	150	227	222	135
Focal Length *(mm)*	35	85	50	18	70	95

High-speed camera coordinates, focal points and settings for the IIHS Small Overlap Frontal Crashworthiness Evaluation.

While many aspects of the imaging process for off-board cameras, including lens calculations, are the same as that of on-board cameras, off-board crash tests do have some key imaging differences. For example, they offer technicians more space and light to work with—making camera size and light sensitivity less of a concern. Due to their location outside the vehicle, off-board cameras also do not have to sustain the same kind of potentially destructive forces that on-board cameras do.



Off-board camera positions for the IIHS Small Overlap Frontal Crashworthiness Evaluation include: overhead (A), rear oblique (B), left side (C), front (D), front oblique (E) and right side (F).

Resolution. Because they are positioned away from the vehicle, off-board cameras typically feature larger sensors and higher resolution—enabling engineers and technicians to easily track and analyze specific objects despite a larger FOV. Because the area to be imaged is larger than on-board shots, a higher resolution camera (4 megapixels or greater) is best suited.

Field of view. Similar to on-board testing, the first step toward figuring out an appropriate FOV is to determine how far away from the camera the object of interest is. Typically, the FOV should be one-quarter vehicle in front and one-quarter vehicle behind. Whether one or multiple cameras are deployed to capture the crash depends on the test's requirements.

Lens selection. Off-board cameras usually take advantage of large sensors and therefore utilize F-mount lenses via an interchangeable lens mount. Since off-board high-speed cameras are not directly involved in crash tests, many technicians prefer to set up their cameras and lenses once. Keeping the camera in the same location for an extended period of time without having to adjust the lens saves on workflow processes and leads to more consistent images.

In off-board situations where lensing needs to be adjusted, Canon EF-mount lenses can be used. These lenses are a good option for overhead recording and other hard-to-reach shots, enabling technicians to adjust the lens aperture and focus via software—sparing personnel from having to climb ladders or enter below ground camera pits to make adjustments.

CONCLUSION

A strong understanding of imaging fundamentals and lensing options can help efficiently produce the high-quality images needed in today's crash tests.

Imaging Fundamentals

It is worth reviewing some key imaging concepts as they relate to capturing crash tests at high speeds. Knowing this information can significantly improve the quality of images taken during tests.

Frame rate and exposure time. While most automotive crash tests are recorded at around 1,000 frames per second (fps), many high-speed cameras are capable of much higher frame rates—especially at reduced resolutions. The other part of the equation is exposure time, or the amount of time each frame is exposed to light. Fast events can occur even within one frame, causing motion blur. Reducing the exposure time captures movement during a smaller, more specific timeframe and eliminates motion blur—but there is a trade-off: reducing the exposure time also reduces the amount of light to the sensor.

Continued on next page.

Imaging Fundamentals (Cont.)

Resolution. Measured in pixels, resolution refers to the amount of detail the camera can capture. Most high-speed cameras have resolutions between 1 and 4 megapixels.

Dynamic range. Dynamic range, or the range of light levels between the darkest and lightest shades in an image, is especially important when there is a need to distinguish between very similar shades. A camera with high dynamic range can distinguish multiple similar shades of black in a foot well, for example, or the multiple shades of white in an airbag.

Bit depth. Bit depth is the number of bits a camera uses to indicate the gray levels of a single pixel. Four-bit depth equates to 16 gray levels, 8-bit depth equates to 256 gray levels and 12-bit depth equates to 4,096 gray levels. A higher bit depth provides more detail, however the tradeoff is that it also generates more data.

Other key points to keep in mind as we review on-board and off-board crash tests include:

- **Focal, or subject plane**—the image area that is in the sharpest focus.
- **Focal length**—the distance, in millimeters, between the optical center of the lens and the sensor. Lenses are identified according to their focal length.
- **Field of view**—the dimensional area of the image at the focal plane.
- **Depth of field**—the distance of acceptably sharp focus to the front and rear of the focal plane.

ABOUT VISION RESEARCH

Vision Research, a business unit of the Materials Analysis Division of AMETEK Inc., designs and manufactures high-speed cameras. The Phantom camera brand is known for unparalleled light sensitivity, image resolution, acquisition speed and image quality—necessities for analyzing high-speed events.

Vision Research offers the broadest range of high-speed cameras to meet the needs of a variety of industries. Used for research and development, the VEO series is popular in academia due to its simple features and budget-friendly models. The ultrahigh-speed series delivers clear images and exact data at the fastest speeds possible. Vision Research has also recently developed a new line of streaming cameras for the machine vision industry that accommodates real-time analysis and long record times.