

A Scientific Approach for Designing Conservative Tests in Vehicle Development

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ABSTRACT

This paper suggests a scientific approach to designing conservative tests based on computer simulation of the influence of the sources of variations. The idea is to design the conservative test so that, even in the presence of variation, there is a high probability that a random test will have a better result than the conservative test. Therefore, if the conservative test meets the requirement, one has a scientific reason to believe that any random test would have a high probability of meeting it. This new approach is illustrated for FMVSS301 80 kph 70% rear offset deformable barrier impact.

INTRODUCTION

An important issue in the area of vehicle safety is how to conduct a conservative test that takes into account the effects of variation in test condition, vehicle content and vehicle build, etc.

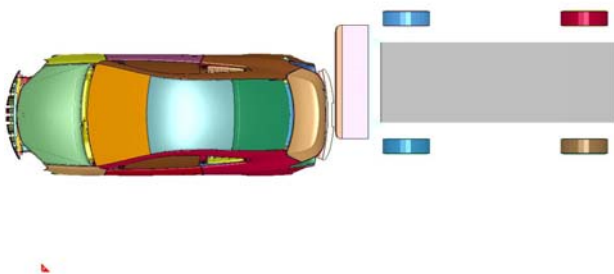


Figure 1. RODB Impact Condition

A common approach of conservative testing is to test for the worst-case scenario based on engineering judgment. Consider the example of FMVSS301 [1] 80 kph

(kilometer-per-hour) 70% Rear Offset Deformable Barrier (RODB) impact. This test is designed to evaluate the fuel system integrity in rear-end collisions. As shown in Figure 1, the vehicle is impacted from the rear by a barrier with a velocity of 80 kph, and the barrier bumper and the vehicle overlap by 70% of the vehicle width. Increasing vehicle mass is a way to make the test more conservative, since the higher the inertia of the vehicle, the more damage would be expected from the rear end structure of the vehicle. Everything else being equal, the heaviest vehicle within the range of vehicle configuration would be tested to determine if the crash performance meets the requirement.

Another common approach is to use a safety margin. Hypothetically, if the requirement limit is 100, a 10% margin could be applied and the new limit with the safety margin would be 90. In the case of RODB impact condition, a safety factor could be added to the test speed, for example, increasing the test speed from 80 kph to 84 kph, which will be equivalent to adding extra 10% impact energy to the test vehicle.

Both approaches, the worst case scenario and the safety margin, are considered "heuristic" or "ad hoc", unless a quantitative analysis of the variations is conducted.

Sources of variation to the crash performance are generally attributed to both vehicle builds and test conditions. The vehicle content variation results from the fact that for a given vehicle model, different powertrain combinations, different suspensions along with different sizes of wheels and tires, and different interior packages are offered. Also, when the vehicle is produced, the sheet metal thickness, the material properties, and the manufacturing process that assembles all the components together, all contribute to the build variation. Finally, when the vehicle is tested for a specific requirement, the test condition will have some variation.

For example, for the RODB impact condition, the test procedure regulates the test speed to be within ± 1 kph of the specified 80 kph. It also allows some variation in the impact location [1].

Although it is a big challenge in the vehicle development phase to understand the effects of all these variations through hardware testing, a finite element model can be developed to help. With the math model, it is possible to estimate the range of variation in the performance, to identify important sources of variation, and to scientifically design a conservative test as we shall demonstrate.

In this paper, we investigate the potential of using higher barrier impact velocity to conduct a conservative test. When the velocity is higher, more kinetic energy is transferred from the barrier to the vehicle. This suggests that if a vehicle performs well at a higher velocity, then it should also perform well at the lower velocity. Nonetheless, one question arises: **How high should the velocity be to have high confidence in the test outcome?**

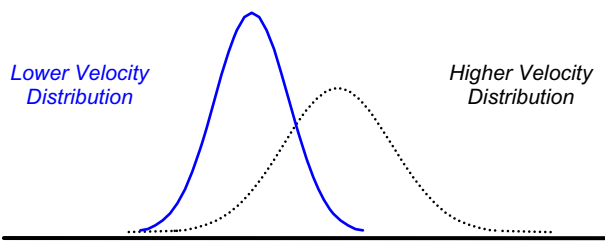


Figure 2. Two Distributions with Significant Overlap

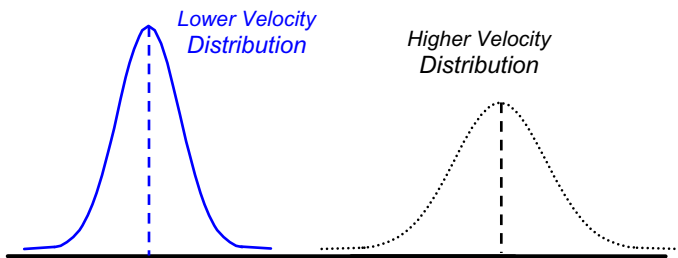


Figure 3. Two Distributions Far-Apart

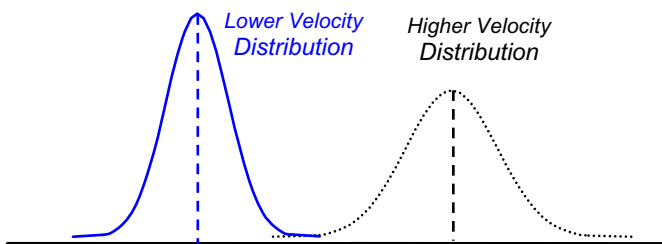
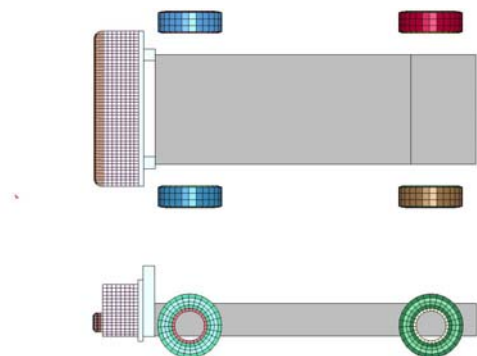


Figure 4. Two Distributions with Little Overlapping

To answer this question, one needs to estimate the variation distribution of the crash performance at both low and high velocities. Consider one scenario in Figure 2, where the two distributions overlap significantly. This means that there is a significant chance that the impact at higher velocity does not cause more damage than that at lower velocity. Another scenario is shown in Figure 3, where the two distributions are far apart. It simply says that the impact at higher velocity always causes more damage than that at the lower one and the design of the vehicle for higher velocity is too conservative, which could become counter-productive in other performance areas. Obviously, it is something in between as shown in Figure 4 that presents a reasonably conservative scenario: the two distributions are separated well enough, but not too far apart. In this paper, we shall define this level of conservativeness using the term “Probability of Under-estimation”, and demonstrate how it may be used to determine the impact velocity.



(Top) Top view (Bottom) Side view
Figure 5. Full Vehicle FE Model



(Top) Top view (Bottom) Side view
Figure 6. Deformable Barrier Model

In this study, a full-vehicle finite element (FE) model (Figure 5) was developed, correlated with hardware tests, and used to study the variation of crash content, the vehicle build, and the test parameters were

chosen as the sources of variation. The simulated deformations of the vehicle rear structure and that of the fuel tank were chosen as the output or response variables. Due to the limitations of the model, the fuel leakage is not directly simulated.

A design of experiment (DOE) study was conducted using the math model instead of hardware. Response surface models (RSMs) for the structural and fuel tank deformations were then fitted using the DOE data and the analysis of variance (ANOVA) was performed to identify the important input variables for each of the responses. Afterwards, Monte-Carlo simulation was performed on the response surface models to estimate the distributions of the responses at different impact velocities. Finally, using the concept of the probability of under-estimation, we determined the appropriate impact velocity for a reasonably conservative test.

FINITE ELEMENT MODEL AND DESIGN OF EXPERIMENT (DOE)

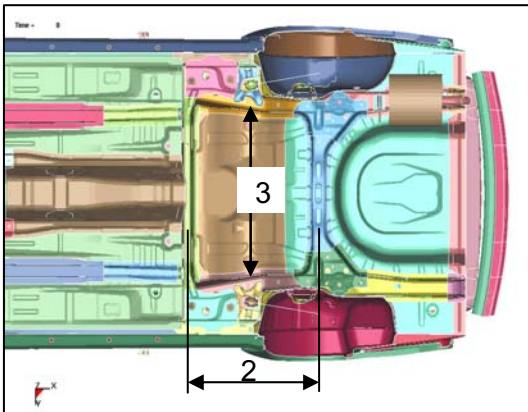
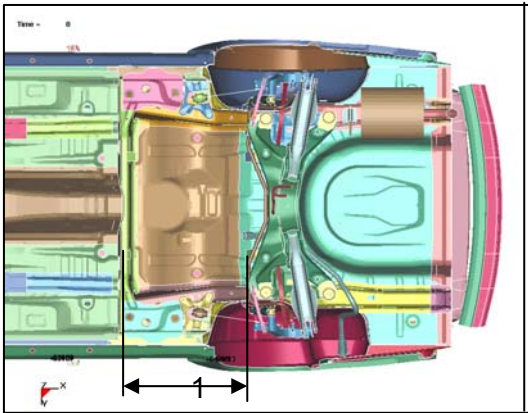
A full vehicle FE structure model (Figure 5) was developed using LS-DYNA [2]. The typical element mesh size is 10mm. Non-structural components, such as rear windshield glass, door glass, exhaust system components, were all included in the model.

Figure 6 shows the FE model for the rear deformable moving barrier. The RODB impact condition requires the barrier to be positioned 70% offset relative to the tested vehicle and the traveling direction of the barrier is parallel to the longitudinal centerline of the test vehicle (Figure 1). The FE model, including the vehicle and the barrier, has approximately 1million elements.

coupon tests. The strain rate effects were included wherever applicable. For example, a cold-roll steel has a static yield strength of 360 MPa, while at a strain rate of $9s^{-1}$, the yield strength reaches 440 MPa. The mass distribution recorded in the test was used to ballast the model until the total mass and the center of gravity in the model match those of the test vehicle. The material tearing including spot weld failure was not considered in this study.

The average velocity at the front rocker predicted by the math model was compared to the test results and it showed good correlation (Figure 7). The correlated model was used in this study.

FMVSS301 requires that the amount of fuel leak during a specific time interval cannot exceed a certain amount after the impact [1]. In practice, the common approach is to allow no fuel leakage. Although the fuel leakage was not simulated, the structural deformation around the fuel tank indicates how much the fuel tank interacts with the surrounding structure. The more the fuel tank deforms, the more likely it will cause fuel leakage.



1 --- Cradle to 4-bar Deformation
2 --- 4-bar to 5-bar Deformation
3 --- Rail Lateral Deformation between 4 & 5 Bars
Figure 8. Structure Repose Variables

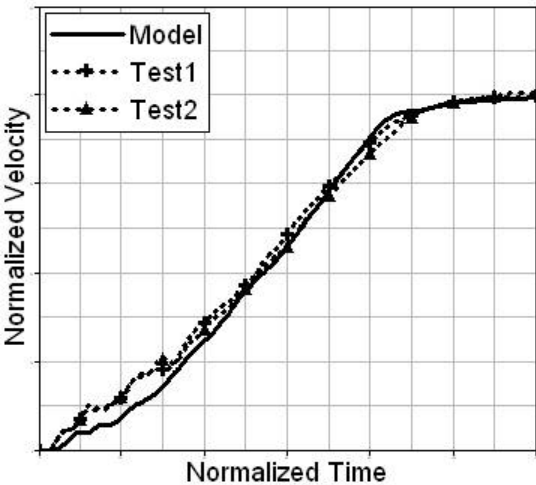


Figure 7. Average Frontal Rocker Velocity

To improve the model fidelity, special attention was paid to material properties and the distribution of mass. The material properties were obtained from a standard material database, which was established through

To assess the structure integrity around the fuel tank, the deformation between the cradle and the 4-bar, the deformation between 4-bar and 5-bar, and the rail lateral