Kinetic Energy Equivalent Speed:

What is it? Why Calculate it? How to Calculate it?

Kinetic Energy Equivalent Speed (KEES) - What is it?

One of the tools of the accident reconstructionist is a Kinetic Energy (K.E.) analysis. In this type of analysis the K.E. transfers, or "losses," are summed for each of the vehicles in order to determine the beginning speeds/velocities of the vehicles. One of these K.E. "losses" occurs in "crushing" a vehicle during impact.

At its most basic, the K.E. Equivalent Speed is the speed equivalent of the K.E. loss. Two common K.E. losses are from damage and from sliding across a surface. The Speed Equivalent of the K.E. loss is calculated with the following equation[1]:

Equation #1:

$$Speed(mph) = \sqrt{\frac{30 * (EnergyLoss)}{(ObjectWeight)}}$$

When calculating a speed from damage, historically the most common "crash test" is a frontal impact into a fixed, non-deformable barrier. In this type of test, the weight of the vehicle is known, the damage is to the test vehicle only, the crush distance can be measured, the pre-impact speed is known, and the post-impact speed is known (assumed) to be zero. In this type of collision, because everything is known, the Energy loss can be easily calculated. Once the Energy loss has been calculated the energy equivalent speed can be calculated. Now, armed with a speed and a crush depth, stiffness values can be calculated. These stiffness values can be the A-B-G values used for a Crash III analysis, the Crush Factor values published in the Expert AutoStats® program, or some other stiffness value, possibly a modification/refinement of the Emori equation[2] for a specific type of collision.

A short digression is now called for. The term "Kinetic Energy Equivalent Speed" to the best of the author's knowledge was first used and published by Daniel W. Vomhof III and Daniel W. Vomhof, Ph.D. in the Expert AutoStats® program in 1991. In most collisions no fixed, non-deformable barrier is involved. Thus the creation of this term, which they believe is a better descriptor of what is being dealt with in the context of vehicle collisions than the more commonly used term "*Equivalent Barrier Speed*," or any other term[3] using the word "*Barrier*." There have been some stated objections to using the term "Kinetic Energy" when discussing this speed, since a spring formula is being used (in the case of the Crash III model's A-B-G values), and a spring model calculates Potential Energy. The creators of the term disagree with this objection for the following three reasons:

1) Potential Energy is stored energy. In the aftermath of a collision, the Potential Energy of the undamaged vehicle has been changed to Kinetic Energy in the crushing of the vehicle,
2) Not all formulas for calculating "Speed from Crush" are based on a spring model, and

3) In most cases, while a Potential Energy model may be the mathematical model, the model is being used to calculate a Kinetic Energy loss, which is what is important to the accident investigator and reconstructionist.

Finally, there has been some objection to the term "Kinetic Energy" because other forms of energy are released in a collision - primarily heat, sound, and light. While these energies are acknowledged, they have not been generally measured, and they are not of (primary) concern to the accident investigator/reconstructionist. Further, these are the energies that the Kinetic Energy is being "changed" into, and thus, the flip side of the energy "coin."

Kinetic Energy Equivalent Speed (KEES) - Why calculate it??

The calculations of the stiffness values become somewhat more complicated when a side impact or rear impact test is conducted, or when a frontal impact test is conducted with a moving "barrier."

Before going further, think about two commercials commonly seen on television in the United States. The first commercial is for a Mercedes. This commercial shows the vehicle approaching a barrier, crushing, and coming to a stop right there at the barrier. This illustrates your common frontal barrier test. The second commercial is for a Saturn. This commercial shows an oncoming barrier approaching the driver's door. At the last moment the camera angle changes to an overhead view and shows the barrier impacting the vehicle and then barrier and vehicle continue out of camera view. This illustrates the problem with the side and rear impact tests. Not ALL of the energy of the moving barrier is used in crushing the vehicle. Only a portion of that energy is transferred or "lost" in damaging the target vehicle.

This is a VERY important and often overlooked point when attempting to calculate vehicle stiffness values based upon crash test data. When the full closing speed is used to calculate stiffness values, erroneously high values are the result. In order to calculate "correct" stiffness values, the speed equivalent to the energy that went into damaging the vehicle MUST be calculated.

Kinetic Energy Equivalent Speed (KEES) - How to calculate it??

One method of calculating the KEES of the lost energy is through the following equation:

Equation #2:

$$KEES=\sqrt{30*\frac{\frac{0.5}{32.2}*\left[IW*\left(\frac{I_{IS}*5280}{3600}\right)^2-(IW)*\left(\frac{I_{PIS}*5280}{3600}\right)^2-(VW)*\left(\frac{V_{PIS}*5280}{3600}\right)^2\right]}{IW}}$$

IW = *Impactor Weight*, I_{IS} = *Impactor Impact Speed*, I_{PIS} = *Impactor Post Impact Speed*
VW = *Vehicle Weight*, V_{PIS} = *Vehicle Post Impact Speed*

In this formula the object weight used as the divisor in calculating the KEES, is the moving impactor barrier weight because that is the object imparting the damage. The more commonly used object weight in the divisor is that of the vehicle being impacted. Which weight to use, and why, will be resolved later in this paper.

In addition to the divisor weight question, there is another problem that needs to be dealt with before this formula can be used. The NHTSA Crash Test database does not currently report the Post Impact Speeds for any of their tests. This is most particularly of concern for any of the NON-FRONTAL (side and rear) impact tests, as well as the frontal impact tests involving a moving impact "barrier." Since this important item of data is not reported, one or more assumptions must be made. The first assumption is that the Impactor and Vehicle reach a common post impact velocity. To help the non-reconstructionist visualize this, it is further assumed that the impactor and vehicle "stick" together post impact, thus illustrating the two vehicles reaching and maintaining a common post impact speed. Finally, it is assumed that there is no rotational energy involved post impact.

With these assumptions, Equation #2 may be simplified to:

Equation #3:

$$KEES=\sqrt{30*\frac{\frac{0.5}{32.2}*\left[IW*\left(\frac{I_{IS}*5280}{3600}\right)^2-(IW+VW)*\left(\frac{PIS*5280}{3600}\right)^2\right]}{IW}}$$

$$IW = Impactor\ Weight,\ I_{IS} = Impactor\ Impact\ Speed$$
$$VW = Vehicle\ Weight,\ PIS = Post\ Impact\ Speed$$

Using the same assumptions, the calculations may be further simplified through the principle of reduced mass. One important aspect of the principle of reduced mass is the idea of frame of reference. If one views the collision from the frame of reference of the impacting barrier, the barrier approaches the vehicle, impacts the vehicle, and then has continuing post impact movement in the direction of its original path of travel. If one views the collision from the frame of reference of the vehicle, the vehicle approaches the barrier,[4] impacts the barrier, and then "rebounds" from the barrier. The rebounding movement has been traditionally ignored in the calculation of stiffness values. The principle of reduced mass, allows for the calculation of the energy loss in the barrier impact[5]. The expanded reduced mass formula is:

Equation #4:

$$Energy_{MaximumDamage} = \frac{0.5 * Mass_{Vehicle_1} * Mass_{Vehicle_2} * V^2_{Closing}}{Mass_{Vehicle_1} + Mass_{Vehicle_2}}$$

$$V_{Closing} = Closing\ Velocity\ (Speed)\ in\ feet\ per\ second$$

Substituting in the NHTSA specific terms for the general terms the formula becomes:

Equation #5:

$$Energy_{MaximumDamage} = \frac{0.5 * Mass_{Impactor} * Mass_{Vehicle} * V_{Closing}^2}{Mass_{Impactor} + Mass_{Vehicle}}$$

$$V_{Closing} = Closing\ Velocity\ (Speed)\ in\ feet\ per\ second$$

When the speed is reported in miles per hour and the weights are in pounds, this formula becomes:

Equation #6:

$$Energy_{MaximumDamage} = \frac{0.5 * \frac{Weight_{Impactor}}{32.2} * \frac{Weight_{Vehicle}}{32.2} * \left(Speed_{Clo}sing * \frac{5280}{3600}\right)^2}{\frac{Weight_{Impactor}}{32.2} + \frac{Weight_{Vehicle}}{32.2}}$$

Simplified the equation reads as:

Equation #7:

$$Energy_{MaximumDamage} = \frac{1089}{65205} * \frac{Weight_{Impactor} * Weight_{Vehicle} * (Speed_{Closing})^2}{Weight_{Impactor} + Weight_{Vehicle}}$$

The KEES is now calculated as:

Equation #8:

$$Speed_{(mph)} = \sqrt{\frac{30 * Energy_{MaximumDamage}}{(ObjectWeight_{(pounds)})}}$$

Using the same reasoning process as before, that the object imparting the damage should be in the divisor, the Object weight to be used is the Vehicle Weight rather than the Impactor Weight (remember, we are assuming the Vehicle hits the barrier). The resulting “final” equation is therefore:

Equation #9:

$$Speed_{(mph)} = \sqrt{\frac{30 * Energy_{MaximumDamage}}{(Vehicle\ \ Weight_{(pounds)})}}$$

We have now seen a logical, rational, explanation where either the Impactor Weight or the Vehicle Weight is the proper weight to use in the divisor. But which is correct??!!??

Kinetic Energy Equivalent Speed (KEES) - Cautions to be aware of:

First caution - again, why calculate the KEES speed?

To illustrate the effect of using the reported impact speed vs. the KEES speed, consider the NHTSA Rear Impact test for a 1988 Chevrolet Cavalier (# 1279). The pertinent data is as follows:

Impactor Weight = 4000 pounds
Vehicle test weight = 3989 pounds
Closing speed = 29.4 mph
average crush depth = 13.1 inches
a "No damage" value of 5 mph
crush width = vehicle width = 65.5 inches.

When one calculates the A-B-G values based upon the closing speed of 29.4 mph, the results are:
A = 457.1, B = 170.7, G = 612.0

Using the same data, the KEES speed = 20.8 mph, and the A-B-G values based on this speed are:
A = 295.3, B = 71.3, G = 612.0

It can be seen that there is a significant difference between the two A-B stiffness results. To get the proper visualization of what is being calculated in the first set of stiffness values, picture a vehicle with steel rods securing the vehicle to the ground at each of the four tires. The Impactor barrier hits the vehicle, and ALL of the impact energy of the impactor barrier goes into the resultant crush of the vehicle. When using these stiffness results for a reconstruction of a rear-ender collision involving a similar Chevrolet Cavalier, a higher than actual speed calculation will be the likely result.

Second caution - which "vehicle" weight should be used in the divisor for the KEES speed calculation?

Again using the data from NHTSA test #1279, what is the difference on the KEES speed between using the Impactor Weight and the Vehicle Weight in the divisor? If the calculated Energy loss = 57663.798, then the KEES speed calculated using the Impactor Weight =20.796 mph, and the KEES speed using the Vehicle Weight = 20.825 mph, a difference of only 0.029 mph. A difference which is not enough to be concerned about, and is in fact practically an invisible difference . . . when the weights are close.

However, let us now apply a principle of ESP[6] (Exaggeration of System Parameters) and substitute your "typical" tractor (also called a "semi-tractor" or "over-the-road tractor") for the impacting barrier, which is the nearest thing the author can think of to a "non-deformable" impactor barrier in a "real" collision. While the vehicle weight remains at 3,989 pounds, the barrier weight now becomes 13,500 pounds which results in a calculated Energy loss of 88900.553. When the ***vehicle weight*** is the divisor the resulting KEES speed is 25.857 mph, and when the ***impactor weight*** is the divisor the KEES speed is 14.056 mph. While both speeds are mathematically correct and valid, this, most would agree, is a SIGNIFICANT difference in speeds.

Which speed is "truly correct"? What is the point? If both speeds are "valid," what does this illustrate?

This example illustrates the point that when calculating the KEES speed, use the divisor weight of the "vehicle" for which the stiffness values are to be calculated.[7] [8] This is the weight to use, NOT because we are pretending it is the object imparting the damage, but because IT is the vehicle upon which the energy loss is acting.

Summation and Conclusions

The concept of a KEES speed, by whatever name it is called, is important. Its calculation is simplified when the collision is into a fixed barrier, much as the speed change from skid is simplified when the ending speed is zero. However, just as when the ending speed is not zero, the speed change from skidding becomes more complicated, so does the calculation of the KEES speed become more complicated when the barrier is not fixed. In order to obtain a correct initial speed when the ending speed from skid is not zero it is important to go through extra calculations. Likewise, if one is going to calculate stiffness values from vehicles in test crashes to be applied to a vehicle involved in a side or rear impact collision, it is just as important to go through the extra calculations to obtain the KEES speed.

The calculations demonstrated have often times either not been made or made incorrectly. In fact this paper came about due to questions arising regarding calculation errors in A-B-G stiffness values in NHTSA test # 1279. As also demonstrated, an incorrect test speed WILL lead to incorrect stiffness values, and thus an incorrect speed calculation in the subject collision.

Finally, it must be remembered that while the NHTSA crash data is usually the best data available, several critical assumptions MUST be made in order to calculate stiffness values for the side and rear of test vehicles. These assumptions may, or may not, be valid. Therefore, the reliance upon the speed calculations made based upon the calculated stiffness values must always be examined carefully by the accident reconstructionist.

1. Throughout this paper, if no units are stated, weights are in pounds and speeds are in miles per hour.

2. "The Investigation of Automobile Collisions with Wooden Utility Poles and Trees" as presented by Joseph Cofone at the S.A.T.A.I. Spring Conference, 3/9-10/2001.

3. For a variety of terms, the reader is referred to DOT/HS 800 624 and the following SAE papers - 680016, 740565, 850256, 850437, 930899, 940914, 2000-01-0462, 2001-01-0499, and 2001-01-0500.

4. Again, refer to the Saturn commercial. As one views the approaching barrier, the viewer does not know if the barrier is approaching the vehicle or if the vehicle is approaching the barrier. We only "know" that the barrier is approaching the vehicle due to our having knowledge not immediately present in the camera shot.

5. The reduced mass principle can be stated as [m1*m2/(m1+m2)]. Mr. Bonnett has further refined this for his applications of determining CEEBS (Crush Energy Equivalent Barrier Speed). Mr. Bonnett discusses this further in an as yet unpublished paper "**Stiffness Coefficients - Energy and Damage"** © George M. Bonnett, JD 2001 All Rights Reserved. It is also discussed in SAE papers 850437, 930899, 2000-01-0462, 2001-01-0499, and 2001-01-0500.

6. I first saw a reference to this term in the book ***Star Driver***, ©1980 by Lee S. Corey. In applying this principle you make some part of what you are working on very big, very small, very fast, very slow, etc. blowing that part totally out of proportion to the rest of what you are working on. This then helps to see problems where they might otherwise not be detected, as in the case of which object weight to use. When both objects are nearly the same weight and the numerical display is only to one decimal place, the difference in speeds are not detected, in both cases for test 1279 "the calculated speed" is 20.8 mph.

7. As a result of work on this paper, the formula used at 4N6XPRT Systems for calculating the KEES speed from the NHTSA crash test data has been modified to:

$$KEES_{MPH} = \sqrt{30 * \frac{\frac{0.5}{32.2} * \left[IW * \left(\frac{I_{IS} * 5280}{3600} \right)^2 - (IW + VW) * \left(\frac{PIS * 5280}{3600} \right)^2 \right]}{VW}}$$

IW = *Impactor Weight (pounds)*, I_{IS} = *Impactor Impact Speed (MPH)*,
VW = *Vehicle Weight (pounds)*, PIS = *Post Impact Speed (MPH)*

8. Further condensation of Equations 7 & 9 results in the following "simplified" equation:

$$KEES_{MPH} = \sqrt{\frac{484}{483} * \frac{ImpactorWeight_{(pounds)} * ClosingSpeed^2_{(MPH)}}{ImpactorWeight_{(pounds)} + VehicleWeight_{(pounds)}}}$$